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K. S. Sterrett, L. S. Stodieck and P. W. Todd**
BioServe Space Technologies

M. H. Kliss
NASA Ames Research Center

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ABSTRACT

The Plant Generic BioProcessing Apparatus (PGBA), a plant growth facility developed for commercial space biotechnology research, has flown successfully on 3 spaceflight missions for 4, 10 and 16 days. The environmental control systems of this plant growth chamber (28 liter/0.075 m²) provide atmospheric, thermal, and humidity control, as well as lighting and nutrient supply. Typical performance profiles of water transpiration and dehumidification, carbon dioxide absorption (photosynthesis) and respiration rates in the PGBA unit (on orbit and ground) are presented. Data were collected on single and mixed crops. Design options and considerations for the different sub-systems are compared with those of similar hardware.

INTRODUCTION

In the past, plant growth experiments in spacecraft have focused mainly on microgravity research, but plants are expected to play an increasing role in advanced life support systems (ALS), where biological systems have a potential role in keeping astronauts alive and healthy (Knott, 1998). Several small plant facilities have been flown to date aboard the U.S. Space Shuttle (Plant Growth Unit, PGU; Plant Growth Facility, PGF; Astroculture™; PGBA) and the Russian Space Station Mir (Svet; Astroculture™). New facilities are planned for near-term use aboard the International Space Station (ISS), such as the Commercial Plant Biotechnology Facility (CBPF), and the Biomass Production System (BPS). Appendix 1 summarizes the characteristics of these facilities. These plant chambers provide only approximately 0.1 m² of growth area, and the constraints of spaceflight, mainly mass, volume and power limitation, have limited the capabilities of current spaceflight-capable systems.

Ground studies and conceptual designs have explored larger, more sophisticated plant facilities, which could play a more important role in controlled ecological life support systems (CELSS) for long-term planetary missions or even aboard the ISS.

For optimal function or for reproducible scientific results in the spacecraft environment, spaceflight plant growth systems require a complex environmental control system. The control system must regulate the atmospheric gas composition (oxygen, carbon dioxide, trace gases, and moisture content), to control the atmospheric conditions (pressure and temperature), to provide light energy for photosynthesis (photoperiod, intensity, spectral composition), and to supply the plants with the appropriate nutrients and water to support photosynthesis, and to compensate for evaporation and transpiration losses. The microgravity environment complicates some of these control functions, such as the requirement for a gravity-independent humidity control system, and a temperature control and cooling system that can operate in the absence of natural convection. Since the spacecraft environment itself is controlled to less stringent requirements than those required for scientific plant research, and since adequate levels of containment have to be provided to protect the health and safety of the astronauts, spaceflight plant chamber atmospheres are typically isolated from the crew cabin. The plant growth area, the plant chamber volume, the environmental condition (oxygen, carbon dioxide, pressure, temperature, humidity, light intensity), and the type and age of plants are all factors which affect the performance requirements and mass flow demands to and from such an isolated plant growth chamber.

Table 1. PGBA spaceflight plant growth chamber characteristics (engineering specifications / limits, see Hoehn et al., 1997, 1996).

Light Intensity (fluorescent)	^a 350 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PAR
Air Temperature Range	18-25°C
Humidity Range (dew point)	60-100% r.H.
Chamber Air Volume	28.3 liter
Usable Growth Area, 25x30 cm ²	0.075 m ²
Max. Theoretical Dehumid. Rate	17.28 liter $\cdot\text{day}^{-1}$ H ₂ O
Max. Water Supply to Roots	17.28 liter $\cdot\text{day}^{-1}$ H ₂ O
Chamber CO ₂ Range	250 – 3,000 ppm
Cabin Air max. Intake Rate	2 liter $\cdot\text{min}^{-1}$
Max. CO ₂ Supply Rate for 500 ppm Target / 3,000 ppm external CO ₂ Concentration	7.2 liter $\cdot\text{day}^{-1}$ CO ₂ (14 gram $\cdot\text{day}^{-1}$ CO ₂)

The authors of this paper have designed, operated and flown in space a plant growth facility named Plant Generic BioProcessing Apparatus, PGBA, during three independent spaceflight missions (Hoehn et al., 1997; Stodieck et al., 1998). This paper focuses on the mass flows within the PGBA plant growth system, namely the capabilities of the system to measure and control atmospheric components (O₂, CO₂, H₂O), and to provide for root zone re-hydration (H₂O, Figure 5). Key performance characteristics and system limitations (based on pump flow rates or external environmental conditions) are listed in Table 1.



Figure 1: The PGBA spaceflight plant growth chamber as flown aboard STS-83. The plant roots are contained in soil (water replenishment) or agar media (no water replenishment, Heyenga, 1997). The plant chamber is sealed from the crew cabin, but receives CO₂-rich cabin air for controlled CO₂ replenishment (Hoehn et al., 1997). (Left) Root tray, (Center) sealed plant chamber and lighting / video system, (Right) plants grown in space flight during STS-83.

ATMOSPHERIC GAS COMPOSITION

Of main concern is the control of carbon dioxide (CO₂) and oxygen (O₂). Depending on light intensity, day-night cycle, and environmental conditions (temperature, humidity, carbon dioxide, oxygen concentration), a net oxygen production and net carbon dioxide removal from the chamber can take place during the 'day'. Some earlier spaceflight plant growth facilities used low light intensities (below the compensation point of approximately 20-80 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, Lawlor, 1990), which resulted in a net oxygen use and net carbon dioxide production even during the day (Figure 2). With higher light intensities now available in the next generation plant growth chambers (PGBA, BPS, CPBF), a net oxygen production can be expected, and carbon dioxide has to be supplied to

the plant chamber atmosphere. Carbon dioxide can be supplied through a pressurized, pure CO₂ system, or through the use of the CO₂-rich cabin atmosphere (standard N₂/O₂ ratio of 78% N₂, ^a21%O₂, <1%CO₂).

The net production of oxygen at higher light intensities will now require a controlled oxygen removal system, as high O₂ concentration can inhibit photosynthesis and, therefore, limit the plant growth at elevated O₂ levels (Figure 3 bottom). The cabin atmosphere, typically controlled to Earth-like conditions of ^a21% O₂, can be used to 'dilute' the increasing O₂ content in the plant chamber, or active oxygen removal systems have to be employed (semi-permeable membrane systems, oxygen absorbers).

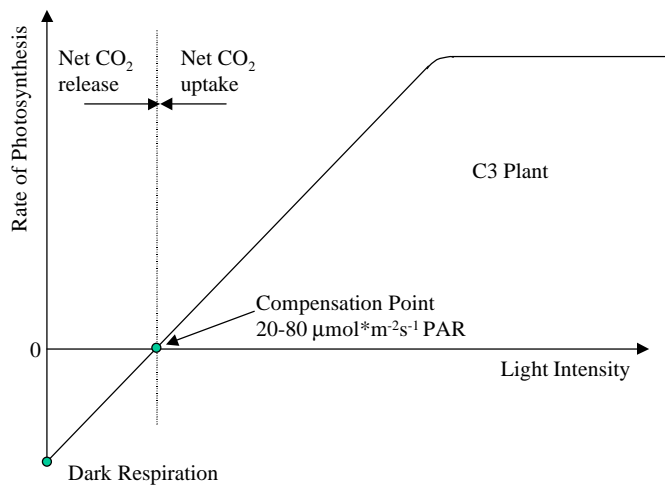


Figure 2. Photosynthesis - simplified carbon dioxide exchange rate as a function of light intensity (C_3 plants). At low intensities and at night, carbon dioxide is produced and oxygen is consumed. At intensities above the compensation point, net oxygen production and net carbon dioxide fixation will take place.

The third function of the gas composition control system, in addition to O_2 and CO_2 control, is the requirement to control potential harmful trace contaminants (such as Volatile Organic Compounds, VOC), that may build up in the sealed environment. Of special concern is the control of ethylene (C_2H_4), which is a strong plant hormone, and affects plant growth at very low concentrations. Adsorption filters (such as activated carbon) or oxidizing converters (such as potassium permanganate, UV catalytic converters) are often used.

CARBON DIOXIDE CONTROL – The CO_2 concentration is typically measured using small infrared gas sensors with an accuracy of 10-30 ppm (full range: 0-4,000 ppm). These sensors measure partial gas pressure, and readings have to be corrected using the absolute pressure at the point of measurement to obtain the more customary volumetric ratio units (parts per million, volume by volume concentration). Various schemes for CO_2 concentration control have been implemented: unpressurized pure CO_2 injection (Astroculture™), pressurized pure CO_2 injection (BPS, CPBF), or injection of CO_2 -enriched cabin air (PGBA).

At night, the increase of CO_2 concentration due to respiration can be limited using scrubbers, such as lithium hydroxide (PGU) or barium hydroxide (PGBA). The control systems require control valves and compressors. Injection of pure CO_2 has the disadvantage that it would require an oxygen separation system, as high O_2 concentrations can limit the photosynthetic rates in some plants (Figure 3B).

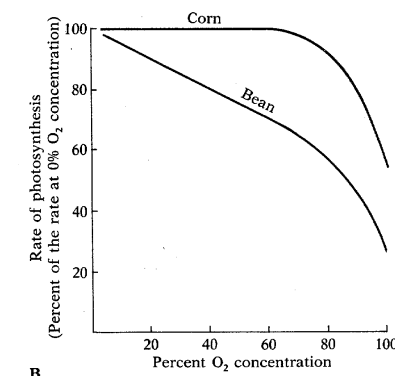
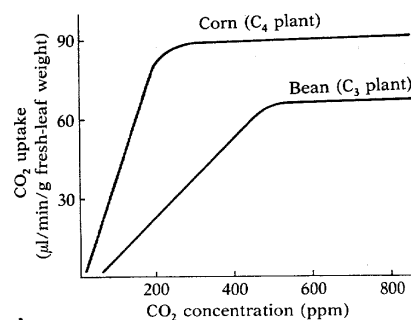


Figure 3. Rate of Photosynthesis as a Function of Carbon Dioxide (A) and Oxygen (B) Concentrations (Keeton, 1979) at specific light intensities.

PGBA Carbon Dioxide Control – Crew cabin carbon dioxide concentrations aboard the Space Shuttle typically range between 3,000 and 6,000 ppm, while oxygen partial pressure is maintained at approximately 220 mbar ($\approx 22\%$ at 1 bar, $\approx 31\%$ at 0.7 bar during EVA). The plant growth chamber CO_2 concentration was controlled for the recent PGBA experiments at 500 ppm (Earth's ambient CO_2 concentration is currently ≈ 350 ppm). The PGBA ATS software (Kuzminsky et al., 1997) uses high-low setpoints (bandwidth control) to allow the constant measurement of rates of photosynthesis and rates of respiration. During the day, the CO_2 concentration was controlled to 500 ppm using CO_2 -rich cabin air injection. At 500 ppm, the chamber was sealed and photosynthesis was allowed to reduce the CO_2 concentration in the sealed chamber down to 465 ppm (35 ppm bandwidth, Figure 4 top). Rates of photosynthesis were calculated from the time between the high and low CO_2 concentration (slope). This process continued throughout the day cycle. Similarly, at night, the CO_2 concentration increased due to respiration. At 600 ppm, the PGBA CO_2 scrubber reduced the concentration back to 565 ppm (35 ppm bandwidth). The time to increase the CO_2 concentration back to 600 ppm corresponds to the rate of respiration (Figure 4 top). The setpoints for CO_2 intake (day) and CO_2 scrubbing (night) can be set independently to different levels, which were 500 ppm and 600 ppm for PGBA during STS-83 and STS-94 (Figure 4 bottom).

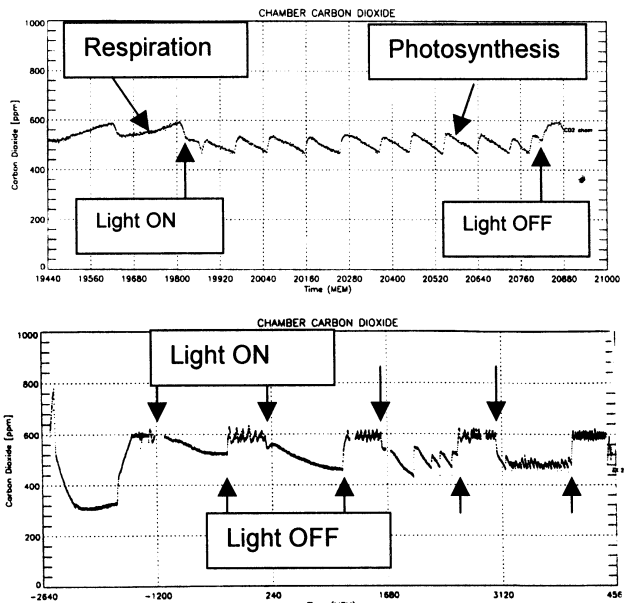


Figure 4. PGBA CO₂ control shown for a single day (top) and 4 days (bottom). (Top) Slopes of respiration and photosynthesis. (Bottom) CO₂ concentration for very young plants, recently transplanted into PGBA. On day 1 and 2, no CO₂ injections were required due to the still low rate of photosynthesis. On day three, 4 CO₂ injections were needed (increased photosynthesis). On day 4, with fully established root systems after transplanting, the 20 individual CO₂ injections are difficult to resolve on the graph.

OXYGEN CONTROL – In a sealed chamber without oxygen removal, oxygen concentrations could reach growth-limiting concentrations (Figure 3 B) within short periods of time, depending on the rate of photosynthesis of the plants inside the chamber (mainly based on plant type and age, chamber volume, CO₂ concentration and light intensity). Therefore, the following system was briefly considered for PGBA as a regenerative method to separate O₂ from the plant chamber (rather than a non-regenerative absorber).

Semi-Permeable Membrane O₂ Separator – The O₂ separation system would have been based on Oxygen-Enriched Air (OEA) membranes, which, to date, have generally been limited to medical uses. Such systems have been proposed for combustion and incineration; however, pressure swing adsorption units are generally more cost effective for such large scale applications. In the medical application, the membrane unit delivers oxygen-enhanced air to an ambulatory patient. The unit is about the size of a portable TV and needs only electricity (and air). In the medical use context, the OEA membrane is competitive with carrying around a bottle of pressurized oxygen. The feed air has to be compressed to between 6 and 12 bar, while the oxygen-enriched air can be collected on the non-pressurized side of the membrane. Liquid water in the feed air needs to be avoided.

Due to the use of CO₂-enriched cabin air with controlled oxygen concentration at ^a22%, the O₂ separator was not required for PGBA operations, as the oxygen concentration equilibrated at approximately the crew cabin O₂ concentrations as explained below.

PGBA Oxygen Control – The PGBA plant chamber is maintained at pressure equilibrium with the ambient cabin atmosphere to minimize structural mass. Relief valves at 0.02 bar differential pressure (0.3 psi_d) ensure that for every volume of CO₂-rich air taken in, equal amounts of air will be expelled from the chamber. Chamber-internal circulation fans guarantee fast mixing between intake air and chamber air (Figure 5). It can be shown that this control strategy will result in a daytime oxygen concentration that is approximately the sum of the external O₂ and the difference of (external – internal) CO₂ concentration (assuming 1:1 ratio of O₂ to CO₂ in photosynthesis). For typical Space Shuttle cabin conditions, the equilibrium O₂ concentration inside the PGBA plant chamber during photosynthesis is therefore 22.25% (22% O₂ + (0.3%-0.05%) CO₂ ⇒ 22.25% O₂). During each cabin air injection (465ppm to 500 ppm), ^a1.2 ml of pure CO₂ are injected into the PGBA atmosphere at 2 liter·min⁻¹ air intake rate.

TRACE GAS CONTROL – The use of sealed environments such as the Space Shuttle crew cabin as well as the sealed plant chamber itself will lead to the accumulation of trace contaminants from materials offgassing. Also, some volatile compounds are produced by the plant itself, such as the very potent plant hormone ethylene (C₂H₄). Offgassing can be minimized using metallic materials rather than plastics with their organic solvents and plasticizers. In nature, the ultraviolet spectrum of the sunlight typically results in oxidation of some of the volatile organic compounds. The artificial lighting systems of spaceflight plant systems provide little if any UV-light, but UV-light activated photocatalytic converters such as the one provided by WCSAR's Astroculture™ system (Bula et al., 1996; Duffie et al, 1995) are easily implemented.

Activated carbon filters are also employed to further limit trace gas or contaminant buildup inside the plant growth chamber. PGBA uses a 150 ml activated carbon filter. The location of the carbon filter within the Atmosphere Treatment System (ATS) has to be carefully considered, as activated carbon acts as a selective filter for carbon dioxide. This leads to an instability of the carbon dioxide control system of PGBA. The CO₂-rich cabin air was first pumped through the activated carbon filter. Instead of letting the carbon dioxide pass into the chamber, the carbon filter saturated to the new equilibrium CO₂ concentration (CO₂ sink). Once the new chamber concentration was reached and CO₂ injection from the cabin stopped, the carbon filter acted as a source of CO₂ as it was equilibrating to the new chamber CO₂ concentration. This led to overshoot in the control system. Subsequently, the carbon filter was removed from the air intake lines and relocated to not expose the carbon filter to these CO₂ concentration swings.

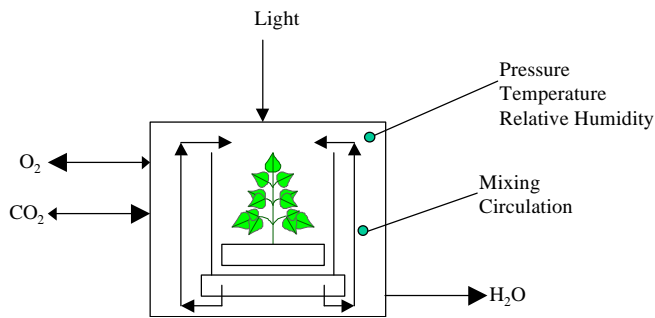


Figure 5. PGBA plant growth chamber with root module insert and deflector walls. Main mass flows to and from the chamber are shown.

FLIGHT VERSUS GROUND CONTROL – During a typical spaceflight mission, two identical PGBA units are operated: a flight unit in space, and a ground control unit for ground (1g) comparison purposes. Ideally, the plants and all environmental conditions in the two units are identical, with the exception of the flight unit being exposed to a microgravity environment (μg), while the ground unit is exposed to nominal gravity (1-g). The flight unit is controlled to a desired environment by the PGBA on-board control computer (Kuzminsky et al., 1997). The ground unit receives the environmental data as recorded by the flight unit through the data downlink capabilities of the Space Shuttle. The ground unit will then attempt to control the ground environment to the actual flight environment, rather than to the ideal, pre-programmed target environment (“master-slave” control). In case of on-orbit deviations from the target environment, the ground unit can now minimize differences between flight and ground environments. During the STS-94 mission, the flight unit experienced larger than expected fluctuations of the CO_2 concentration due to the instabilities caused by the activated carbon filter as described above. Based on the data received from orbit (in 1 minute increments, with periodic data drop outs of ≈ 20 minutes due to orbital conditions), the ground unit was able to very accurately duplicate the conditions (Figure 6). During data drop-out periods, the ground units controlled to the last received data point (‘horizontal wave’ lines in Figure 6 = ground data).

WATER CYCLE

Water enters the plant chamber atmosphere due to evaporation from the root zone, the soil, and from plant tissues, but predominantly due to transpiration through the stomata. Evaporation losses can be minimized with proper root zone enclosure as shown in the PGBA nutrient packs (Heyenga, 1997; Figure 1, left). Water is required by the plants for photosynthesis, evaporative cooling, to transport dissolved nutrients to and within the plant, and to maintain structural integrity of the growing plant (Turgor pressure). Control systems to manage the water budget of a plant facility are typically separated into a humidity control system, and a nutrient and water delivery system. Dew point control is most often used to control the air moisture content, where surface tension or

centrifugal forces are used to separate the condensing water from the air stream in the microgravity environment. The water flux is typically high when compared to the overall water content and mass of the plant chamber system, so it becomes necessary to return the condensed water in the humidity control system back to the nutrient delivery and root hydration system. Coupling the dehumidification and water recycling system increases the risk for contamination and spread of diseases across the plants. Appropriate microbial check valves have been installed to minimize that risk in PGBA.

PGBA HUMIDITY CONTROL – To deal with the unique concerns of microgravity fluid management, PGBA utilizes a humidity control system based on the porous plate technology that is a modification of a design by the Wisconsin Center for Space Automation and Robotics (Zhou et al., 1997, 1996). A porous, sintered stainless steel plate, primed with water and covering a water filled cavity, is cooled below the dew point to condense water from the air stream. Priming is very important to ensure the proper function of the system (Scovazzo et al., 1997). The system is first flushed with CO_2 , which is easily dissolved in the next system flush of de-aerated water. This ensures that all entrapped gases are removed from the system. The cavity behind the porous plate is maintained at a slight negative relative pressure by redundant solenoid micro-pumps. The pumps draw the condensed water through the pores in the plate into the water reservoir behind. The suction pressure does not affect the rate of dehumidification (Scovazzo et al., 1997). The suction pressure is chosen such that sufficient margins of safety remain to prevent air intrusions into the membrane. At the chosen membrane pore size of $0.2 \mu\text{m}$, the PGBA dehumidifier suction pressure was controlled to -0.034 bar ($-0.5 \text{ psi}_\text{g}$; the $0.2 \mu\text{m}$ membrane bubble pressure is 2.7 psi_d). The steady-state relative humidity in PGBA (air moisture content) is a function of the porous plate temperature only. Humidity is controlled by adjusting the plate temperature and maintaining constant suction pressure. While the membrane temperature controls and limits the relative humidity, the volumetric flow rate of the pumps (max. $17.28 \text{ liter} \cdot \text{day}^{-1}$) limit the mass throughput. The maximum theoretical capacity of the PGBA system is much higher than actual observed rates, which are less than $200 \text{ ml} / \text{day}$ at $80\% \text{ rel. humidity}$ and 25°C .

The PGBA plant chamber air (28.3 liter) contains 0.688 grams of water moisture at 25°C and $100\% \text{ relative humidity}$ (saturation, Table 2). The daily rate of water condensation (at $80\% \text{ rel. humidity}$, 25°C) during STS-94 was $100\text{-}200 \text{ grams/day}$. After 16 days of spaceflight, the entire water content of the plant nutrient packs ($\approx 30 \times 100 \text{ ml}$, Heyenga, 1997) was ‘recycled’ once through the dehumidification and root zone rehydration (NDS) system. The actual recycled water volume was $\approx 3,000 \text{ ml}$. The loss of dehumidification, due to cooling or pump failure, would result in reaching $100\% \text{ rel. humidity}$ within $\approx 5 \text{ minutes}$ at the required dehumidification rate of 200 ml/day to maintain steady state ($0.688 \text{ g} / 200 \text{ ml/day} = 4.9 \text{ minutes}$).

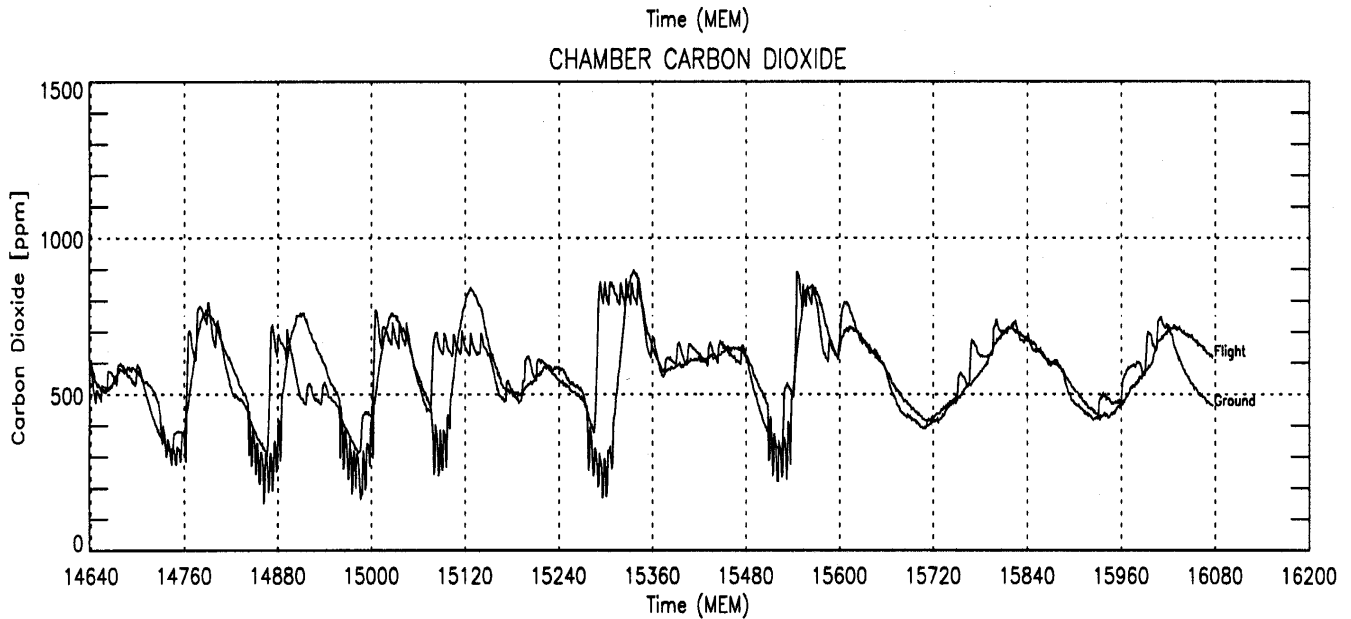


Figure 6. PGBA Flight and Ground CO₂ Concentration. The PGBA flight unit data is downlinked to Earth, where the ground unit attempts to reproduce the flight environmental conditions as closely as possible to enable comparisons of 'flight versus ground' plant growth results.

Table 2. Water content of air and the amount of moisture in the PGBA chamber air at saturation (28.3 liter). From Dubbel, 15th edition, 1983.

Pressure=1013 mbar	Moisture content at 100% rel. humidity	PGBA H ₂ O content in air
T=10°C, ρ=1.243 kg m ⁻³	7.88 g H ₂ O / kg air	0.277 g H ₂ O
T=20°C, ρ=1.195 kg m ⁻³	15.19 g H ₂ O / kg air	0.514 g H ₂ O
T=22°C, ρ=1.186 kg m ⁻³	17.24 g H ₂ O / kg air	0.579 g H ₂ O
T=25°C, ρ=1.170 kg m ⁻³	20.77 g H ₂ O / kg air	0.688 g H ₂ O
T=30°C, ρ=1.146 kg m ⁻³	28.14 g H ₂ O / kg air	0.913 g H ₂ O

PGBA ROOT SYSTEM HYDRATION – The nutrient delivery system receives the condensate water collected from the porous plate humidity control system and feeds it back to the plants via the root tray. The root tray contains a distribution matrix to resupply water to each of 30 nutrient pack positions. Each position has a single port covered by a membrane that supplies water from the distribution matrix to the bottom of a nutrient pack. There is a layer of wicking material between the supply port and the nutrient packs to even the pack-to-pack water distribution. The plant roots are contained within the nutrient packs, filled with either agar or aggregate that provide nutrients specifically formulated for each species or for specific experimental requirements such as radioisotope labeling (Figure 1; Heyenga, 1997; Hoehn et al., 1997; Stodieck et al., 1998).

PGBA WATER CYCLE – The humidity and nutrient delivery system are coupled through the micropump manifold. Water can be pumped from the humidity system to the nutrient delivery system and vice versa. Two pumps, for redundancy, pull suction pressure on the humidity control

system to draw condensed water through the cooled porous plate and furnish it directly to the root tray. Two additional pumps can pull water from an external reservoir and provide the water to the humidity control system to humidify the chamber when necessary. This is rarely needed while plants are growing in the sealed chamber, but is necessary during plant installation while the chamber is open to the environment. The remaining pump is configured to pump water from the dehumidifier to a storage bag instead of to the root tray. Each pump has a stroke volume of 50μl to accurately maintain the desired suction pressure in the dehumidifier.

CONCLUSION

Advances have been made to better characterize and control the environment in spaceflight plant growth chambers. The improved environmental conditions available in the next generation plant growth chambers will support healthier plant growth. The higher light levels pose new challenges to the environmental control systems, especially the mass flow intensive atmosphere and water cycle control systems, as well as the thermal control system (Horner et al., 1997). Despite improved control capabilities, on-orbit deviation from the desired environmental conditions are sometimes possible. Performing ground control experiments in a duplicate chamber that can accurately reproduce the on-orbit conditions has proven very beneficial for the STS-94 flight of PGBA, where the identical ground unit tracked the down-linked on-orbit environmental conditions very precisely.

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ADDITIONAL SOURCES

Characteristics of current and near-term spaceflight plant growth chambers have been collected from various sources (anon., 1983; anon., 1998; Bula et al., 1996; Duffie et al., 1995; Hoehn et al., 1996, 1997, Zhou et al., 1996, 1997) and are summarized in Appendix 1.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

ARC: NASA Ames Research Center.
ASC: Astroculture™, designed and operated by WCSAR under Code UX grant.
ATS: Atmosphere Treatment System.
A/D: analog to digital converter.
ALS: Advanced Life Support.
b: blue light.
BPS: Biomass Production System, designed by Orbitec under NASA KSC contract.
CELSS: Controlled Ecological Life Support System.
CO₂: Carbon Dioxide.
CPBF: Commercial Plant Biotechnology Facility, designed by WCSAR under Code UX grant.
D: depth.
DAC: Data Acquisition and Control.
DIO: Digital Input / Output.
EVA: Extra-Vehicular Activity.
fr: far-red light.
g: Earth gravity, 9.81 ms⁻².
H: height.
H₂O: Water.
IR: infrared light.
ISS: International Space Station.
KSC: NASA Kennedy Space Center.
LED: Light Emitting Diode.
MLE: Middeck Locker Equivalent, maximum internal dimensions are D20.320"xW17.337"xH9.969".
MEM: Mission Elapsed Minutes.
N₂: Nitrogen.
NASA: National Aeronautics and Space Administration
NDS: Nutrient Delivery System.
OEA: Oxygen-Enriched Air membranes.

O₂: Oxygen.
P: Pressure.
PAR: photosynthetic active radiation (measured between 400-700 nm wavelength).
PGBA: Plant Generic BioProcessing Apparatus.
PGC: Plant Growth Chamber
PGF: Plant Growth Facility, designed by Arthur D. Little and NASA KSC, under NASA KSC contract.
PGU: Plant Growth Unit, designed by Lockheed under NASA Ames / NASA KSC contract.
POCC: Payload Operations and Command Center.
psi: Pounds per Square Inch pressure.
r: red light.
rH: relative humidity.
SMAC: Space Maximum Allowable Concentration.
STS: Space Transportation System.
T: Temperature.
TEC: Thermoelectric Controller or Cooler.
UV: ultraviolet.
UX: NASA Code UX, Division of Space Development and Commercial Research.
VDC: Volts Direct Current.
VOC: Volatile Organic Compound.
W: Width or Watt.
WCSAR: Wisconsin Center for Space Automation and Robotics.

APPENDIX 1

Space Plant Chamber →	Plant Growth Unit,	Astroculture™,	Plant Growth Facility,	MIR Plant Growth Facility, SVET (=light)	Plant Generic BioProcessing Apparatus, PGBA	Biomass Production System, BPS	Commercial Plant Biotechnology Facility, CPBF
↓ Description / Criteria	PGU	ASC	PGF	(=light)	Apparatus, PGBA	BPS	Facility, CPBF
Development / Operations	Lockheed / NASA-ARC, later KSC 1982	WCSAR NASA Code UX 1992	A.D. Little NASA-KSC 1997	Bulgaria / Russia 1990	BioServe Space T. NASA Code UX 1996	Orbitec NASA KSC > 1999 (UF-2)	WCSAR NASA Code UX > 2000
First Flight	8 (flown)	8 (flown 5 times, 2 w/8 plants)	8 (flown)	8 (flown)	8 (flown 3 times w/ plants)	3 (critical design)	3 (critical design)
NASA Technology Readiness	< 70 lbm.	< 70 lbm.	< 70 lbm.	-	< 120 lbm.	< 230 Watt	< 280 lbm.
Payload Mass	< 130 Watt	150 / 100 Watt	< 130 Watt	-	< 230 Watt	< 230 Watt (planned)	< 660 / 1200 Watt
Payload Power	1 MLE	1 MLE	1 MLE	-	2 MLE	2 MLE	4 MLE
Overall Dimension	(W18"xH10"xD20")	(W16"xH9"xD19")	(W18"xH11"xD20")	(W18"xH22"xD20")	(W18"xH22"xD20")	(W18"xH22"xD20")	(W36.5"xH22"xD24")
Chamber Dimensions	6 x (W7xD1.6xH9)	2 x (W4"xD4"xH7")	6 x (W7"xD1.6"xH9")	(W6"xH20"xD12")	W10" x D12" x H12"	4 x (W6"xD7"xH6")	19"x18"x18"H
Chamber Volume	8.4 liter	3.2 liter each	10.4 liter	20 liter	28.3 liter	16.6 liter	80 liter
Total Growing Area	0.05 m ²	0.021 m ²	0.055 m ²	0.075 m ²	0.075 m ²	0.104 m ² (all 4)	0.2 m ²
Plant Chambers	6, only 5 with ATS	1-2	6, only 5 with ATS	1	1	1, 2 or 4	1-4
Temperature Control	None	TEC	TEC	None	TEC	TEC	TEC
Humidity Control	T > ambient	T > 22°C	T > ambient	T > ambient	T > 22°C	T > 20°C	T > 15-40°C
	None (Sealed)	TEC	Passive	None	TEC / dew point	TEC / dew point	TEC / dew point
	rH ≈ 100%	rH > 70%		RH > ambient	rH > 60%	rH > 60%	rH > 60-95%
Light Intensity (PAR)	60 μmol m ⁻² s ⁻¹	300 μmol m ⁻² s ⁻¹	220 μmol m ⁻² s ⁻¹	240 μmol m ⁻² s ⁻¹	> 350 μmol m ⁻² s ⁻¹	300 μmol m ⁻² s ⁻¹	500 μmol m ⁻² s ⁻¹
Light Source	Fluorescent	LED (red+blue)	Comp. Fluorescent	Fluorescent	Comp. Fluorescent	Fluorescent	LED (r, b, fr)
Chamber Closure	Originally Closed; Now open with ATS.	Closed	Open, microbial filters	Open	Closed	Closed	Closed
Active CO ₂ Control:	Some (with ATS):	Yes:	Some (with ATS):	No:	Yes:	Yes:	Yes:
Chamber CO ₂ Supply	From cabin air	CO ₂ injection	From cabin air	Open to Cabin	Act. cabin air inject.	CO ₂ injection	CO ₂ injection
Chamber CO ₂ Scrubber	None	None	None	None	BaOH scrubber	-	-
CO ₂ Range	None	300-2,000 ppm, 2 g CO ₂ supply at ambient pressure	None	MIR ambient: Typical 5,000 ppm	250-3,000 ppm: typical 500 ppm day 600 ppm night	300-2,000 ppm: 20 g pressurized CO ₂ supply	300-2,000 ppm:
Oxygen Control	None	None	None	Open to ambient	Control to ambient	None	None
Trace Contaminant Control / Volatile Organic Compound	None, only with use of ATS	Yes: photocatalytic converter	None, only with use of use ATS	None: open to ambient	Yes: photocatalytic system, activated C.	Yes: photocatalytic converter	Yes: photocatalytic converter
Root matrix	saturated foam, or agar	Porous tubes with matrix	Saturated foam, or agar	Zeolite / Balkanite	Nutrient Pack: agar or soil aggregate withmatrix (tbd) wicking matrix	Porous tubes with matrix (tbd)	Porous tubes with matrix (tbd)
Root Zone Re-hydration / Nutrient Delivery System	None	Closed circulation loop	None	MIR Space Station water supply	Humidity condensate recycling	Closed loop, ISS H ₂ O replenish	Closed loop
Nutrient Composition Control	None (preflight)	None (preflight) or Zeoionics (time release)	None (preflight)	Zeoionics (time release)	None (preflight) (time release nutrient pack)	None (preflight) or Zeoionics, or replenish	None (preflight) or Zeoionics, or replenish
Plant Access / Harvesting	On Orbit	Ground Only	On Orbit	On Orbit	Optional for On Orbit	On Orbit	On Orbit
Data Acquisition and Control	Some DAC	DAC, 32 channels	Some DAC	DAC, 18 ch.	DAC, 32 channel	DAC	DAC
	No downlink	Downlink	No Downlink	-	Downlink	Downlink	Downlink
	No Command	No Command	No Command	-	Remote Control	Remote Control	Remote Control
	No Video	Y video	No Video	-	2 Video camera	Video, 2 each	Video