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BioServe Space Technologies

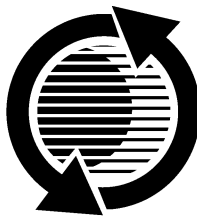
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# Atmosphere Composition Control of Spaceflight Plant Growth Chambers

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## ABSTRACT

Spaceflight plant growth chambers require an atmosphere control system to maintain adequate levels of carbon dioxide and oxygen, as well as to limit trace gas components, for optimum or reproducible scientific performance. Recent atmosphere control anomalies of a spaceflight plant chamber, resulting in unstable CO<sub>2</sub> control, have been analyzed. An activated carbon filter, designed to absorb trace gas contaminants, has proven detrimental to the atmosphere control system due to its large buffer capacity for CO<sub>2</sub>. The latest plant chamber redesign addresses the control anomalies and introduces a new approach to atmosphere control (low leakage rate chamber, regenerative control of CO<sub>2</sub>, O<sub>2</sub>, and ethylene).

## INTRODUCTION

Photosynthesis and subsequent plant growth is strongly controlled by light and atmospheric oxygen and carbon dioxide concentration. Spaceflight plant growth chambers are typically located within the crew cabin atmosphere, maintained mostly at 101 kPa absolute pressure. CO<sub>2</sub> concentration in the crew cabin, however, is elevated when compared to Earth ( $\approx$ 350 ppm) and fluctuates with crew activity between 2,000 and 7,000 ppm typically. On the International Space Station (ISS), CO<sub>2</sub> concentrations of  $\approx$ 700 ppm are advertised. In addition to CO<sub>2</sub> fluctuation, materials offgassing into the crew cabin can produce elevated levels of volatile organic compounds (VOC, trace contaminants) such as ethylene, a strong plant growth hormone. Most spaceflight plant chamber designs therefore feature an isolated plant chamber atmosphere to allow for cabin-independent, accurate and preferably regenerative control of CO<sub>2</sub> and O<sub>2</sub>, as well as scrubbing of VOC. During the 'day', plants typically exhibit a net conversion of CO<sub>2</sub> into O<sub>2</sub>, while at 'night', O<sub>2</sub> is consumed and CO<sub>2</sub> is produced. With higher light intensities and longer plant growth periods on

the International Space Station, the total mass of CO<sub>2</sub>-O<sub>2</sub> conversion increases, and regenerative methods become beneficial. As long as Earth-like CO<sub>2</sub> concentrations are desired ( $\approx$ 350 ppm), the crew cabin can be used as a source of CO<sub>2</sub> (typically 2,000-7,000 ppm on NSTS, 700 ppm on ISS). Similarly, the almost constant O<sub>2</sub> cabin concentration (21%) provides a convenient source and sink of oxygen for the plant chamber. Conversion of CO<sub>2</sub> into O<sub>2</sub> for crew consumption represents a first step towards a bio-regenerative atmosphere revitalization system.

The PGBA greenhouse, designed and operated by the authors, has utilized a cabin air based CO<sub>2</sub> control system during three space flights (Hoehn et al., 1996, 1997a, b, 1998, 2000). The use of CO<sub>2</sub>-enriched cabin air eliminates the need of a pressurized CO<sub>2</sub> supply system, and at the same time controls the O<sub>2</sub> levels inside the plant chamber to the oxygen concentrations available within the spacecraft, thus eliminating the need of an oxygen scrubber. Continuous pure CO<sub>2</sub> injection into an isolated plant chamber could otherwise result in elevated oxygen concentrations, detrimental to photosynthesis of C<sub>3</sub> plants, and, at very high O<sub>2</sub> concentrations, even to C<sub>4</sub> plants (Keeton, 1979).

PGBA, a sealed plant growth facility developed for commercial space biotechnology research, has flown aboard three different Space Shuttle missions and successfully grew a total of 50 plants of different species on orbit. The PGBA life support system provides computerized atmospheric, thermal (Horner et al., 1996) and humidity control (Scovazzo et al., 1997), as well as lighting and nutrient supply (Heyenga, 1997; Hoehn et al., 2000, Kliss et al., 2000) to the plants. Only the atmosphere composition system will be analyzed here.

During the last flight of PGBA (STS-94), an unexplained control anomaly occurred in the CO<sub>2</sub> control system. CO<sub>2</sub> concentrations fluctuated and the control system

appeared unstable. Upon return to Earth, the system appeared functional and stable again. However, the system does not contain any apparent gravity-sensitive equipment and all control components appeared to work properly. This anomaly led to a renewed analysis and test series of the atmosphere treatment system (ATS), the results of which will be presented here. Analysis quickly showed that the activated carbon filter, designed to absorb trace gas contaminants, acts as a large buffer of CO<sub>2</sub>, and can cause control system instabilities. The buffer capacity of the activated carbon filter also affects the calculated rates of photosynthesis and respiration.

## PLANT CHAMBER ATMOSPHERE CONTROL

**BACKGROUND AND REQUIREMENTS** – Several plant growth systems have been developed or are under development for spaceflight (summarized in Hoehn et al., 1998): the Plant Growth Unit (PGU) and its successor, the Plant Growth Facility (PGF), the AstroCulture™ System (ASC), the Plant Generic BioProcessing Apparatus (PGBA), the Bulgarian greenhouse aboard MIR (SVET), the Biomass Production System (BPS), the Commercial Plant Biotechnology Facility (CPBF), and the Plant Research Unit (PRU) for ISS.

To compare plant growth results between Earth and space grown samples, and to ensure reproducible plant experimentation, plant experiments are conducted in a controlled environment. The main atmospheric variables affecting plant growth are temperature, humidity, carbon dioxide, oxygen and trace gas elements. The cabin concentration of CO<sub>2</sub> fluctuates with crew activity, while volatile organic compounds (VOC), harmful to plants, may be present in the crew cabin. The following atmosphere control systems have been used for spaceflight plant systems:

- Open (SVET) to cabin atmosphere – no control, only monitoring. Difficult to compare flight to ground data, unpredictable plant growth results.
- Open (PGU with ATS) – not controlled, but passive adsorption of CO<sub>2</sub> and trace contaminants.
- Sealed (PGU) – only works for short periods of time and low light intensities, otherwise rapid depletion or accumulation of O<sub>2</sub>, CO<sub>2</sub> and trace gases.
- Isolated (PGBA, PGF, BPS, CPBF) – uses controlled intake of cabin air or pressurized pure CO<sub>2</sub> gas to maintain setpoint for CO<sub>2</sub> and O<sub>2</sub> concentration.

For additional information on measurements of gas exchange in plant chambers, see Wheeler et al., 1992: Characterization of Gas Exchange in Plant Growth Chambers.

CO<sub>2</sub> sources: pressurized vs. cabin enrichment – Carbon dioxide is consumed during photosynthesis and converted to biomass. The net loss of CO<sub>2</sub> during plant growth can be replenished from stored CO<sub>2</sub> sources (pressurized or liquefied CO<sub>2</sub>, ≈6 MPa at room

temperature), or using ambient CO<sub>2</sub>. On Earth, CO<sub>2</sub> concentrations are ≈350 ppm, whereas in spacecraft concentrations are typically elevated, with 2000-7000 ppm on the Space Shuttle (NSTS) and 700 ppm expected on the International Space Station (ISS). It is therefore possible to draw CO<sub>2</sub>-rich cabin air into a sealed plant chamber to replenish CO<sub>2</sub>, as long as a chamber concentration below cabin air is acceptable. The smaller the difference between cabin and plant atmosphere, the more open the system. Intake of cabin air will automatically dilute the photosynthetically produced oxygen inside the chamber to that of the crew cabin. Since the cabin atmosphere will never exceed 1% CO<sub>2</sub> (safety / health limit by NASA), the oxygen concentration within the plant chamber could, at most, be 1% higher than the O<sub>2</sub> concentration in the cabin (typically 21%).

The use of pressurized CO<sub>2</sub> requires additional safety systems to control the CO<sub>2</sub> flow (redundant regulator, safety bleed valves), as well as resupply of CO<sub>2</sub> replacement tanks. The O<sub>2</sub> produced by photosynthesis from pressurized CO<sub>2</sub> would then need to be separated from the plant atmosphere, and ejected to the crew cabin. This would be the basic function of a bioregenerative atmosphere treatment system for astronauts. Alternatively, the produced oxygen could be absorbed (oxidized) or converted (catalytic combustion) to produce CO<sub>2</sub>. Even with moderate light levels above the compensation point (above ≈ 80 μmol photons m<sup>-2</sup>s<sup>-1</sup> PAR), CO<sub>2</sub> is quickly depleted.

To simplify the ATS and to avoid requiring resupply, the PGBA ATS utilizes CO<sub>2</sub>-rich cabin air to replenish the internal carbon dioxide concentration. To minimize risk from VOC from the crew cabin, all intake air is scrubbed by an ethylene scrubber and an activated charcoal filter.

CO<sub>2</sub> sinks: consumable vs. regenerative – At night, plant respiration will increase the CO<sub>2</sub> concentration. Due to the small size and subsequent small buffer volume of current spaceflight chambers, CO<sub>2</sub> concentration increases rapidly and needs to be limited. Larger chambers typically have enough buffer volume to not require CO<sub>2</sub> control at night. Several CO<sub>2</sub> scrubbers are commercially available or are used in spacecraft, such as Lithium Hydroxide or Barium Hydroxide. Submarines and future spacecraft are typically designed to use regenerative CO<sub>2</sub> scrubbers, such as molecular sieves. To simplify the PGBA ATS and to avoid requiring additional dedicated powered hardware, PGBA uses a non-regenerative Barium Hydroxide CO<sub>2</sub> scrubber (BaOH). If the CO<sub>2</sub> concentration within the plant chamber exceeds prescribed levels, the ATS air flow is passed through the BaOH scrubber and CO<sub>2</sub> is chemically bound. The current scrubber can maintain adequate CO<sub>2</sub> levels, given typical respiration and chamber leakage rates in PGBA, for approximately 120 days (typical ISS tour of duty).

O<sub>2</sub> sources: cabin air – Oxygen is readily available from the crew cabin. During standard operations, the crew cabin is maintained at 101 kPa and 21% O<sub>2</sub>. Only during EVA is the cabin pressure reduced to 70 kPa and O<sub>2</sub> concentrations increased to 30%. Oxygen can be depleted quickly in a sealed or isolated plant chamber and needs to be replenished. Currently, only cabin air is used for O<sub>2</sub> replenishment.

O<sub>2</sub> sinks: consumable vs. regenerative – In the past, plant chambers provided only very low light intensities and oxygen production was not an issue during short spaceflight missions. With increased light intensities and extended growth periods with rapidly growing plants, oxygen concentrations need to be controlled. While diluting the oxygen concentration with cabin air is the simplest solution, only O<sub>2</sub> scrubbers, separators or concentrators would allow accurate and independent oxygen control. Several membrane-based systems were evaluated, but simplicity dictated control by dilution with cabin air for PGBA.

Trace gas control: consumable vs. regenerative – Volatile organic compounds (VOC), and especially ethylene, are of great concern for plant growth. VOC may be introduced by incoming cabin air, produced from outgassing of non-metallic components within the plant chamber (plastics, tubing, glue), or present as trace gases produced by the plants themselves. Several methods have been applied in small plant chambers as well as commercial plant production and shipping facilities to address this problem:

- Adsorption on activated charcoal.
- Oxidation by Potassium Permanganate (KMnO<sub>4</sub>), commercially available as Purafil™ (Activated Alumina impregnated with Potassium Permanganate).
- Photocatalytic conversion on Titanium Dioxide using UV-light.

PGBA employs both a photocatalytic ethylene scrubber (developed by WCSAR, see for example: Zhou et al., 1998; Bula et al., 1996; Duffie et al., 1995), and an activated charcoal filter. The ethylene scrubber and activated charcoal are located such that all air, both plant chamber air and cabin air taken in during CO<sub>2</sub> replenishment, is filtered (Figure 1).

**PGBA ATMOSPHERE CONTROL SYSTEM** – Anomalies in controlling the chamber CO<sub>2</sub> concentration occurred during the last Space Shuttle mission to the effect that the CO<sub>2</sub> controller was, under some circumstances, unable to keep the chamber CO<sub>2</sub> concentration within given limits. Also, a recently developed computer model, which simulates the current ATS design, indicates that PGBA is not able to supply enough CO<sub>2</sub> to plants with high photosynthesis rates (Robinson, 1999). Furthermore, Table 1 shows that calculated photosynthesis rates from PGBA are unusually small

compared with numbers found from other sealed plant growth chambers.

Table 1. Comparison of Photosynthesis Rates, scaled to PGBA Growth Area (References: 1. Kitaya et al., 1991. 2. Wheeler et al., 1998, 3. Wheeler et al., 1992, and 4. Kliss et al., 1996).

Plant	Light Level	CO <sub>2</sub> Conc.	Photosynthesis Scaled to PGBA	Ref
Lettuce	240	400	≈450	1
Soybean	420-870	1000	≈115	2
Wheat	500-700	1000	≈66-89	3
Lettuce	200	1000	≈25	4
PGBA Mixed Crop	280 (μmol / m <sup>2</sup> / s)	500 (ppm)	≈5 (μg CO <sub>2</sub> / s)	

These events indicate that the current design of PGBA's Atmosphere Treatment System (ATS) may be limited or may not work reliably under all possible circumstances. Extensive tests were performed to identify the reason for the on-orbit anomaly and to suggest an improved ATS control system.

CO<sub>2</sub> concentration within the ATS loop – During normal operation (no CO<sub>2</sub> injection), the ATS loop CO<sub>2</sub> concentration, measured in partial pressure units, corresponds to the chamber CO<sub>2</sub> concentration (in ppm) when the ATS loop backpressure is taken into account. When the air intake valve opens, the loop CO<sub>2</sub> concentration increases to the injected CO<sub>2</sub> concentration due to back flow. After the air intake valve closes, it takes about 3 minutes for the loop CO<sub>2</sub> concentration to return to the chamber CO<sub>2</sub> concentration. This delayed return to equilibrium can be explained by a combination of the following effects:

- Response time and variability of the CO<sub>2</sub> sensors.
- Flow rate differences in the two modes of ATS operation.
- The time constant of the chamber.

CO<sub>2</sub> sensors – The current ATS design (Figure 1) uses two infrared CO<sub>2</sub> flow-through sensors placed within the ATS-loop (GMM12, Vaisala). One sensor measures the plant chamber CO<sub>2</sub> concentration (0..3,000 ppm), and the second sensor measures the incoming cabin air CO<sub>2</sub> concentration (0..30,000 ppm). The cabin concentration is used to calculate the required valve opening time for feed-forward CO<sub>2</sub> intake control.

Since infrared absorption CO<sub>2</sub> sensors specifically measure CO<sub>2</sub> - mole density (partial pressure) rather than the typical volume percentages used by plant scientists (ppm), their readings may vary according to absolute pressure and temperature changes. These effects can be eliminated by applying the ideal gas law

and using the measured temperature and pressure of the gas at the sensor. While temperature changes can be compensated for easily, pressure changes may occur abruptly whenever valve actuations occur within the ATS, such as the air intake valve or the BaOH CO<sub>2</sub> scrubbing valve. The redirected flow changes the back pressure of the system, thus changing the absolute pressure in the CO<sub>2</sub> sensor assembly. Response times in the sensor assembly of 30 s, together with the changes in absolute and partial pressures, complicate interpretation of sensor readings, even when compensating for pressure. The difference in response time may lead to temporary misreading or misinterpretation of the actual chamber CO<sub>2</sub> concentration, resulting in inappropriate CO<sub>2</sub> controller commands.

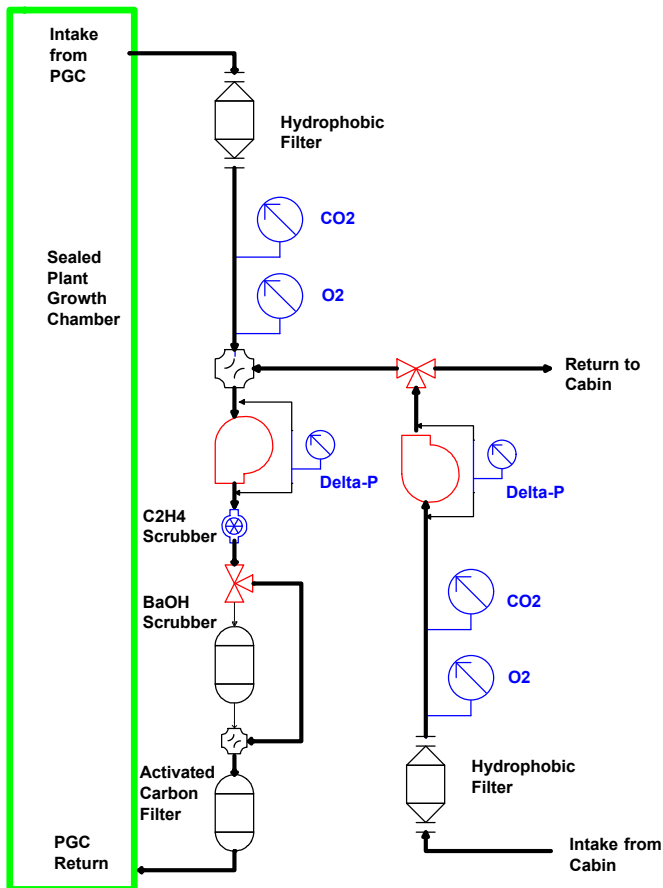


Figure 1. The PGBA Atmosphere Treatment System (ATS). Air is drawn from the plant chamber through O<sub>2</sub> and CO<sub>2</sub> sensors, through the compressor, into the photocatalytic ethylene scrubber, CO<sub>2</sub> scrubber (if needed), activated carbon filter and back into the plant chamber. A second loop on the compressor transports CO<sub>2</sub>-rich cabin air through the cabin air CO<sub>2</sub> sensor, and if necessary, into the first (plant-chamber internal) loop, otherwise the cabin air is returned to cabin (CO<sub>2</sub> measurement only).

Flow rates within the ATS loop – In flight configuration, PGBA only measures the differential pressure across the compressor head and not the actual flow rate (limited

sensor availability). However, the relation between flow rate and pressure differential are known. For ground research, the flow rates through the ATS loop branches have been measured accurately with inline sensors. The flow rate within the loop (air intake valve closed) has been measured at 4.2 L/min. The flow rate of the air intake branch into the ATS loop (air intake valve open) has been measured at 5.1 L/min. Using the flow rate within the ATS loop (4.2 L/min), calculations show that it takes about 8 minutes to recirculate the total air volume of the PGBA chamber once ( $28.3 \text{ L} / 4.2 \text{ L/min} = 6.6 \text{ min}$ ).

The design of a feed forward CO<sub>2</sub> control system for PGBA is complicated by the lack of direct measurement of flow rate in the flight configuration. Flow rate has to be derived indirectly from the measured pump head differential. Furthermore, the back pressure may change over time as the activated charcoal and Barium Hydroxide beds saturate. The difference between intake (5.1 L/min) and loop (4.2 L/min) flow rates demonstrates this effect of changing back pressures. During air intake at 5.1 L/min, part of the air may actually flow 'backwards' through the sensor system into the plant chamber unfiltered (no check valve in place).

Chamber's CO<sub>2</sub> time constant – When the air intake valve is opened for a specified time, resulting in the injection of a certain amount of CO<sub>2</sub> into the plant growth chamber, observations show that it takes about 3 minutes for the chamber to equilibrate to a new steady-state CO<sub>2</sub> concentration (10..90%). This 3-minute delay is the time constant of the chamber, which depends on the time required for the added CO<sub>2</sub> to mix throughout the chamber (via two blowers internal to the plant chamber) and to be transported back through the ATS to the sensors. The time constant plays an important role in the CO<sub>2</sub> controller design. It is not possible at present to lower the time constant by increasing the mixing rate in the chamber due to the limitation of air flow rate to less than  $0.1 \text{ m s}^{-1}$  in the plant area to minimize thigmotropic responses. Note that the time constant of 3 minutes was measured without the activated carbon filter. With the activated carbon filter in place, the time constant may exceed 10 minutes, which will be discussed in more detail.

CO<sub>2</sub> replenishment rate – During the 'day', plants absorb CO<sub>2</sub> and use photosynthesis to convert it to O<sub>2</sub>. In a closed plant growth chamber, depleted CO<sub>2</sub> must be replenished to the chamber air in order to maintain a desired CO<sub>2</sub> setpoint. The previously mentioned ATS computer model predicts that PGBA is not able to provide sufficient CO<sub>2</sub> replenishment for high photosynthesis rates. Achieving sufficient replenishment would require either increasing the air intake flow rate or drawing from a CO<sub>2</sub> source with a higher concentration.

Opening the air intake valve for a certain amount of time causes the chamber CO<sub>2</sub> concentration to increase by a corresponding value. Experiments have been performed using different valve open times while measuring the

resulting increase in the steady-state chamber CO<sub>2</sub> concentration. As expected, the data obtained show a linear relationship between the CO<sub>2</sub> source concentration and the resulting replenishment rate for a set air intake flow rate. Using the measured intake CO<sub>2</sub> concentration, the chamber size of PGBA, and the air intake flow rate, the CO<sub>2</sub> replenishment rate can be calculated:

$$\text{CO}_2\text{\_RR} = 3.295 * 10^{-5} * \text{CO}_2\text{\_c} * \text{AFR} \quad (1)$$

CO<sub>2</sub>\_RR = CO<sub>2</sub> replenishment rate in mg CO<sub>2</sub> s<sup>-1</sup> of valve opening time  
 CO<sub>2</sub>\_c = CO<sub>2</sub> concentration of the incoming air in ppm  
 AFR = air intake flow rate in L min<sup>-1</sup>

For an incoming CO<sub>2</sub> concentration of 3,000 ppm and an AFR of 5.1 L min<sup>-1</sup>, Equation (1) predicts that PGBA can provide a CO<sub>2</sub> replenishment rate of 0.504 mg CO<sub>2</sub> s<sup>-1</sup>.

Equation (1) has been verified by several experiments and becomes particularly useful when calculating photosynthesis rates.

CO<sub>2</sub> scrubbing rate – During the night, plant respiration produces CO<sub>2</sub> and the chamber CO<sub>2</sub> concentration increases. When the concentration exceeds desired levels, CO<sub>2</sub> must be removed from the chamber air. CO<sub>2</sub> is 'scrubbed' from the air by directing the ATS air flow through a Barium Hydroxide (BaOH) filter, where carbon dioxide is absorbed. In order to maintain a fixed setpoint, BaOH has to scrub the CO<sub>2</sub> faster than the highest possible plant respiration rate. The BaOH scrubber should be dimensioned such that it can absorb the CO<sub>2</sub> produced throughout an entire mission, otherwise manual scrubber exchange becomes necessary.

The rate at which BaOH can remove CO<sub>2</sub> from the sealed chamber was determined by measuring the time required to scrub a specific amount of CO<sub>2</sub> from the sealed chamber. The capacity of the scrubber was experimentally determined to be:

$$\text{CO}_2\text{\_SR} = 0.1 \text{ mg CO}_2 \text{ s}^{-1} \quad (2)$$

CO<sub>2</sub>\_SR = CO<sub>2</sub> scrubbing rate in mg CO<sub>2</sub> per second of valve opening time.

Wheeler et al (1998) reported a maximum plant respiration rate of approximately 0.02 mg CO<sub>2</sub> s<sup>-1</sup> when scaled to the plant growth area of PGBA. Hence, the CO<sub>2</sub> scrubbing rate of PGBA is greater than five times the reported maximum respiration rate and therefore is adequately sized, even after taking CO<sub>2</sub> leakage rates into account, as will be shown.

Assuming the maximum respiration rate of 0.02 mgCO<sub>2</sub> s<sup>-1</sup> in PGBA and a night duration of 8 hours, Equation (2) indicates that 0.576 g CO<sub>2</sub> must be scrubbed per night. For a 120 day mission, this results in a cumulative amount of 70 g CO<sub>2</sub>. The entire BaOH scrubber (170 g BaOH) can absorb up to 74 g of CO<sub>2</sub>

(per manufacturer: 0.435 g CO<sub>2</sub> absorbed per gram of BaOH).

Activated carbon filter – The above CO<sub>2</sub> replenishment and scrubbing rates were investigated with the activated carbon filter bypassed. The activated carbon filter is normally a permanent part of the ATS loop (see Figure 1). The activated carbon filter resides within the ATS loop to remove trace gas contaminants which may be harmful to plants from both the chamber and incoming air. While determining the response time of the PGBA growth chamber it became apparent that the activated carbon filter has a significant influence on the response time and hence the CO<sub>2</sub> control logic. Without the activated carbon filter, the chamber response time is about 3 minutes during injection of CO<sub>2</sub>, and about 10 minutes when scrubbing CO<sub>2</sub> (assuming 1,000ppm to be scrubbed). With the activated carbon filter in the ATS loop, the response times increase to 10 minutes during CO<sub>2</sub> injection and more than 30 minutes when scrubbing CO<sub>2</sub>. In addition, the injection time of CO<sub>2</sub> required to increase the chamber CO<sub>2</sub> concentration by a certain amount was considerably larger with the activated carbon filter in place. Similarly, substantially more CO<sub>2</sub> had to be scrubbed to reduce the chamber concentration by a certain amount. These observations indicate that the activated carbon filter acts as a large CO<sub>2</sub> buffer.

During air intake, the injected CO<sub>2</sub>-rich air has to travel through the activated carbon filter before it can reach the chamber. The activated carbon filter absorbs CO<sub>2</sub> from the incoming air, preventing the chamber from immediately increasing in CO<sub>2</sub> concentration. When the activated carbon becomes saturated, CO<sub>2</sub> enriched air then passes through the filter into the chamber. It is difficult to determine the exact amount of CO<sub>2</sub> buffered in the activated carbon filter.

When air intake ceases, the plants absorb the CO<sub>2</sub> from the chamber air, decreasing the concentration in the ATS loop. The decreased CO<sub>2</sub> concentration in the air passing through the activated carbon causes the absorbed CO<sub>2</sub> to release into the chamber. This buffered CO<sub>2</sub> entering the chamber offsets the observed photosynthesis rate, making it appear lower than actuality.

During scrubbing, CO<sub>2</sub>-depleted air from the BaOH scrubber passes through the carbon filter, again releasing absorbed CO<sub>2</sub> such that a decrease in CO<sub>2</sub> concentration cannot be initially observed. Only after the carbon filter has been depleted of CO<sub>2</sub> will the chamber concentration decrease.

Additional experiments have been performed to quantify the effects of humidity on the CO<sub>2</sub> buffer capacity of the carbon filter. The above-mentioned experiments were conducted with dry chamber air (about 20% rH) and CO<sub>2</sub>-enriched air was supplied from tanks (bone-dry). Additional tests were performed with humidified air at about 85% rH, and the chamber air was controlled to about 60% rH. However, neither the response times

during injection nor during scrubbing of CO<sub>2</sub> changed (10 minutes during injection, 30 minutes during scrubbing, using the carbon filter). Air humidity did not affect the performance in the ranges tested. The activated carbon more than triples the chamber response times in terms of CO<sub>2</sub> control. Furthermore, the exact amount of CO<sub>2</sub> the activated carbon absorbs and releases are not yet quantified. As a result, all previously calculated photosynthesis rate calculations need to be adjusted for the amount of CO<sub>2</sub> buffered.

**CO<sub>2</sub> control software** – The PGBA CO<sub>2</sub> control software is designed to maintain the chamber CO<sub>2</sub> concentration at a 500 ppm setpoint during the day, and 600 ppm at night (Figure 2). Each setpoint has a hysteresis of 35 ppm (draw-down) to allow for the calculation of rates of photosynthesis and respiration. While designed as a feed-forward controller, the software also has a feed-back safety shutoff. However, the software simply executes every 5 seconds and does not account for the chamber response time. While this control has been tested successfully over several plant cycles on ground, it is possible that the controller becomes unstable under certain conditions, as happened during the STS-94 mission. An example may illustrate this behavior:

Assume the chamber CO<sub>2</sub> concentration is below the daytime setpoint. The controller opens the air intake valve to increase the CO<sub>2</sub> concentration. At the next execution, 5 seconds later, the controller measures the chamber CO<sub>2</sub> concentration. Due to the chamber response time of 10 minutes (with the activated carbon filter), the chamber CO<sub>2</sub> concentration has not yet increased. Hence the controller continues to inject CO<sub>2</sub>.

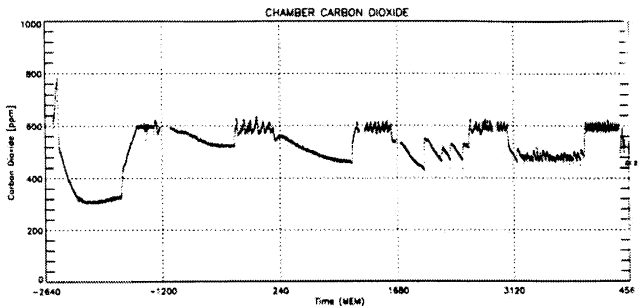


Figure 2. PGBA CO<sub>2</sub> control (5 days) with day and night time set points of 500 and 600 ppm, respectively.

This procedure continues until the chamber CO<sub>2</sub> concentration begins to increase and finally reaches the setpoint. Since at that point the carbon filter had been saturated with CO<sub>2</sub>-enriched air, the filter continues to give off CO<sub>2</sub> and the chamber CO<sub>2</sub> concentration overshoots the setpoint. This activates the BaOH scrubber, which scrubs CO<sub>2</sub> in an attempt to restore the setpoint, but overshoots again due to the chamber response time. This repeated overshooting may lead to instabilities. This control instability has now been reproduced under some circumstances, but it still remains mysterious why those patterns only occur

occasionally. The instability did not occur during pre-mission testing, but did occur during the STS-94 mission while on-orbit only (stable once on ground and prior to flight).

**CO<sub>2</sub> leakage rate** – In order to calculate photosynthesis and respiration rates accurately, it is essential to know the exact CO<sub>2</sub> leakage rate of the ‘sealed’ plant growth chamber. Leakage points exist in all interfaces of fittings and sensors, and especially across the external ATS dual-head compressor. Two experiments were performed to determine PGBA’s CO<sub>2</sub> leakage rate, both at an ambient CO<sub>2</sub> concentration of ≈400 ppm (mean with a standard deviation of 13 ppm). Tests were conducted without an absolute pressure difference between the plant growth chamber and ambient air. In the first experiment, the chamber was purged of CO<sub>2</sub> by filling it with nitrogen until the chamber CO<sub>2</sub> concentration was extremely low. The chamber was then allowed to equilibrate to room conditions as external room air leaked into the chamber, raising the CO<sub>2</sub> concentration.

In the second experiment, the chamber was filled with CO<sub>2</sub> until the chamber CO<sub>2</sub> concentration reached about 4,000 ppm. The chamber equilibrated to the lower ambient CO<sub>2</sub> concentration over 4 ½ days (Figure 3). Taking data from both experiments and looking at various CO<sub>2</sub> concentration changes versus the corresponding time elapsed, Equation 3 was used to calculate leakage rates. The results showed a leakage rate for PGBA between 108% day<sup>-1</sup> and 150% day<sup>-1</sup>, with a mean of 132% day<sup>-1</sup>, and a standard deviation of 11 % day<sup>-1</sup>.

$$LR = \ln \left[ \frac{(C1 - Ca)}{(C2 - Ca)} \right] * \frac{1}{t} * 1440 \frac{\text{min}}{\text{day}} * 100\% \quad (3)$$

LR = leakage rate in % day<sup>-1</sup>  
 C1 = initial chamber CO<sub>2</sub> concentration  
 C2 = chamber CO<sub>2</sub> concentration after time t  
 Ca = ambient CO<sub>2</sub> concentration (mean)  
 t = time elapsed in min

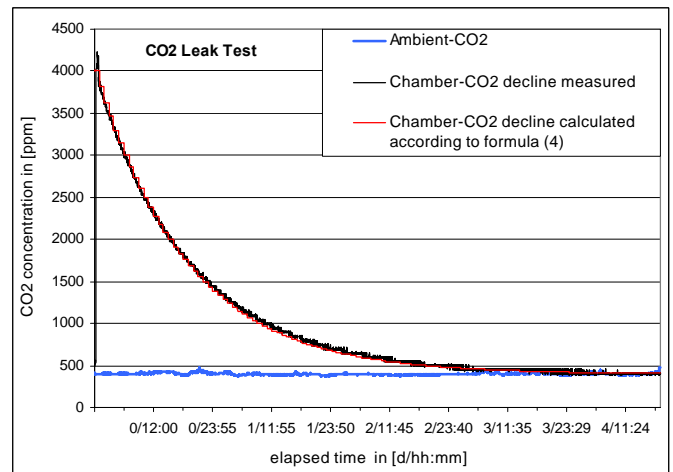


Figure 3. Chamber CO<sub>2</sub> decline vs. time due to CO<sub>2</sub> leakage rate with the fully operational PGBA ATS.

The LR is a measure of the seal integrity within the ATS plumbing, and is useful in comparing leakage rates with other chambers. The leakage rate in Figure 3 is for the fully operational system. Without the ATS compressor running, the chamber has a leakage rate of  $\approx 35\%$  day<sup>-1</sup>. With a high initial CO<sub>2</sub> concentration, the chamber behavior over time shows an exponential decline in CO<sub>2</sub> concentration as it equilibrates to the ambient according to the following relationship (valid for shown PGBA tests, derived from equation 3):

$$C_2 = C_a + \left[ (C_1 - C_a) \cdot e^{(-0.54 \cdot \frac{C_a}{C_1}) \cdot t} \right] \quad (4)$$

C<sub>2</sub> = CO<sub>2</sub> concentration of the chamber at time t.  
 C<sub>1</sub> = CO<sub>2</sub> concentration of the chamber at t=0  
 C<sub>a</sub> = mean ambient CO<sub>2</sub> concentration  
 t = elapsed time in h

Differentiating (4) results in the following equation:

$$\frac{dC_2}{dt} = -0.54 \cdot \left( \frac{C_a}{C_1} \right) \cdot (C_1 - C_a) \cdot e^{(-0.54 \cdot \frac{C_a}{C_1}) \cdot t} \quad (5)$$

Equation 5 is the slope of the declining chamber CO<sub>2</sub> concentration, hence the CO<sub>2</sub> leakage rate versus time.

Using C<sub>1</sub> = 4,000 ppm, C<sub>a</sub> = 400 ppm and t = 8 h, at which time the chamber CO<sub>2</sub> concentration was exactly C<sub>2</sub> = 3,000 ppm, equation (5) calculates a CO<sub>2</sub> leakage rate of 126 ppm per hour.

It should be noted that on-orbit, where the chamber concentration is  $\approx 500$  ppm and the external cabin concentration is  $\approx 3,000$  ppm, the CO<sub>2</sub> leakage would be into the chamber. In all cases, the driving force for CO<sub>2</sub> leakage is the CO<sub>2</sub> concentration gradient between the cabin and the chamber.

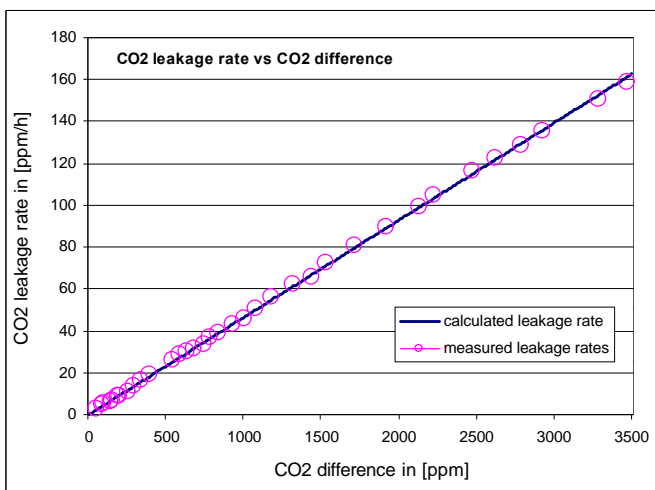


Figure 4. CO<sub>2</sub> leakage rate vs. CO<sub>2</sub> difference between the chamber and ambient air.

For convenience in calculating photosynthesis and respiration rates, the leakage rate should be expressed in terms of CO<sub>2</sub> difference between chamber CO<sub>2</sub>

concentration and ambient CO<sub>2</sub> concentration, a quantity that can be easily measured. Using the measured data from the second experiment and equation (5), it is possible to calculate the actual leakage rate at each elapsed time step (recorded every second). Incorporating the CO<sub>2</sub> difference between the chamber and ambient air for each time step, the leakage rate can be expressed in terms of the driving CO<sub>2</sub> difference. This results in a linear correlation between CO<sub>2</sub> leakage rate and CO<sub>2</sub> difference between the chamber and ambient (Figure 4), from which the following formula was derived (valid for PGBA tests as described here):

$$LR = 4.65 \cdot 10^{-2} \cdot d\_CO_2 \quad (6)$$

LR = leakage rate in ppm h<sup>-1</sup>  
 d\_CO2 = CO<sub>2</sub> difference between the chamber and ambient air in ppm, defined d\_CO2 = C<sub>a</sub>-C<sub>c</sub>

Checking (6) for correctness results in:

$$d\_CO_2 = 400 \text{ ppm} - 3,000 \text{ ppm} = -2,600 \text{ ppm}$$

$$LR = 4.65 \cdot 10^{-2} \cdot -2,600 \text{ ppm} = -121 \text{ ppm/h}$$

This corresponds with the result obtained previously using Equation 5.

Converting Equation 6 to a more convenient form for calculation of photosynthesis and respiration gives:

$$LR^* = 9.193 \cdot 10^{-4} \cdot d\_CO_2 \quad (7)$$

LR\* = leakage rate in  $\mu\text{g}(\text{CO}_2) \text{ s}^{-1}$   
 d\_CO2 = CO<sub>2</sub> difference between the chamber and ambient in ppm

Equation 7 can be used directly when calculating photosynthesis or respiration rates simply by adding the leakage rate multiplied by elapsed time to the amount of CO<sub>2</sub> injected during daytime or subtracting the leakage rate multiplied by the elapsed time from the amount of CO<sub>2</sub> scrubbed at night.

If the CO<sub>2</sub> difference is small, as it typically is in the laboratory on Earth, the resulting leakage rate is so small that it often can be neglected when calculating photosynthesis or respiration rates. On orbit, where the CO<sub>2</sub> difference is often large (500 ppm to 3,000 ppm), the resulting CO<sub>2</sub> leakage rate may become significant and needs to be taken into account.

**CONCLUSION AND SUGGESTED DESIGN CHANGES –** Testing of the PGBA atmosphere treatment system in pursuit of the on-orbit anomaly resulted in the following design changes to eliminate instabilities.

**CO<sub>2</sub> sensor** – To reduce potential leakage points and to eliminate potential errors due to absolute pressure changes in the aspirated atmosphere treatment system, a new diffusion-type sensor has been placed within the plant chamber (Vaisala). The internal air circulation within the chamber allows for fast responses without relying on

the slower compressor-driven flow ( $4 \text{ L min}^{-1}$ ). The chamber absolute pressure is conveniently measured, and the  $\text{CO}_2$  volumetric concentration can be calculated from partial (IR- $\text{CO}_2$  sensor) and absolute pressure (gauge) readings.

**Activated carbon filter** – The large activated carbon filter present in the original PGBA atmospheric control system acted as a  $\text{CO}_2$  buffer. Controlling the chamber  $\text{CO}_2$  in the presence of the buffer with the current feed-forward or feedback control system is extremely difficult or impossible. The activated carbon filter is still needed for VOC control, and thus redesign of the ATS loop is necessary. First, the activated carbon filter is relocated away from the air intake, and second, a proportional air intake instead of batch intake of  $\text{CO}_2$  is implemented. The activated carbon now simulates a larger chamber, but does not equilibrate to the air intake or scrubbed air. This stabilizes the control logic. The proportional control attempts to find a steady-state air intake rate to compensate for photosynthesis or respiration. It is currently implemented as a pulse-width modulated proportional controller, but this system is limited by lifetime of the air intake valve. Future redesign will compensate for this by using a proportionally controlled gate valve.

**$\text{CO}_2$  control approach** – The chamber response time can be improved by locating the  $\text{CO}_2$  sensor within the chamber. Additionally, the software should account for the chamber response time of approximately 3 minutes. It is expected that the current ‘push-pull’ controller will be replaced with an appropriately tuned proportional controller.

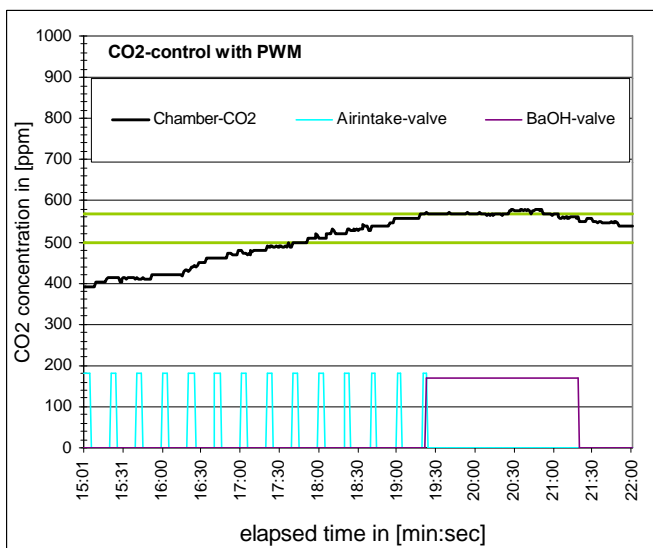


Figure 5. New  $\text{CO}_2$  controller approach: Pulse Width Modulation (PWM) to accomplish a proportional control of  $\text{CO}_2$  Intake.

A proportional control algorithm, using pulse width modulation (PWM), was implemented for testing, using the current air intake valve (Figure 5). The pulse width

controller repeatedly injects one pulse within each fixed timeframe (frequency). The width of the pulse can be controlled to any duration from zero to the entire length of the timeframe (Figure 4). Thus, at the two extremes, the pulse width may be zero and no  $\text{CO}_2$  will be injected at all, or the pulse width can equal the timeframe and  $\text{CO}_2$  will be injected continuously. Continuous injection will determine the maximum photosynthesis rate that PGBA can support.

Several experiments have been performed with the new PWM proportional controller, both with and without plants. In initial tests the PWM controller successfully maintained a set chamber  $\text{CO}_2$  concentration to within +70 ppm and -50 ppm (Figure 6), using a timescale of 20 seconds and only 20 discrete time steps. With a higher resolution PWM, and further tuning of the proportional controller, the accuracy can be improved (proof of concept only to date).

**Photosynthesis rates and respiration rates** – Calculation of photosynthesis and respiration is now based on the measured flow rate, known concentration of the injected air, and duty cycle of the PWM controller. This is an improvement compared to the previous method of analyzing the draw-down slopes in the push-pull control system. The final flight implementation targets a proportional flow rate actuator with actual mass flow measurement of the intake stream.

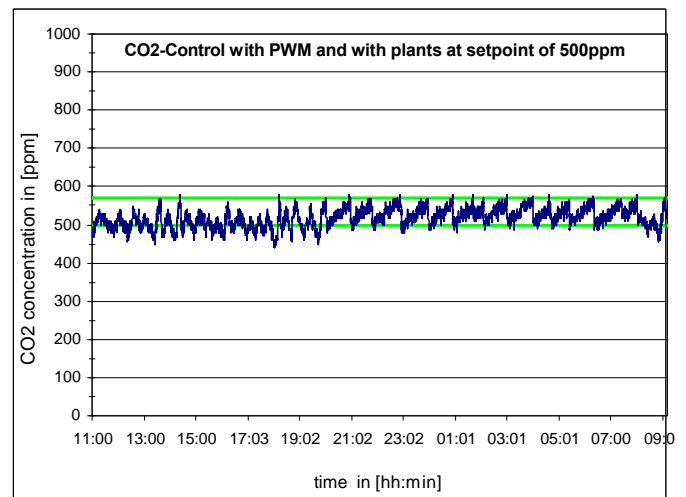


Figure 6.  $\text{CO}_2$  concentration control around a given setpoint using proportional PWM control (20 second period, 20 discrete steps in 1 second pulse width only).

**Computer model and system limits** – The computer model was improved to include leakage rate, corrected air intake flow rates, and the new proportional control strategy. The model predicts that the PGBA ATS should be stable with the photosynthesis rates and respiration rates as measured with candidate plants. Higher photosynthesis rates are still possible with the proportional controller, but have not been tested with actual plants.

The highest photosynthesis rate supported by PGBA while maintaining the chamber CO<sub>2</sub> concentration at the 500 ppm setpoint depends on the cabin (replenishment) CO<sub>2</sub> concentration. A cabin CO<sub>2</sub> concentration of 3,000 ppm would allow PGBA to sustain a maximum photosynthesis rate of about 500 μg CO<sub>2</sub> s<sup>-1</sup>. If the cabin CO<sub>2</sub> concentration is reduced to 700ppm (as advertised for the International Space Station), PGBA can sustain a maximum photosynthesis rate of 117 μg CO<sub>2</sub> s<sup>-1</sup>. The maximum respiration rate calculated to be sustainable by PGBA with a 600 ppm CO<sub>2</sub> concentration setpoint is 100 μg CO<sub>2</sub>/s.

## CONCLUSION

The discussed tests and analysis of the PGBA ATS control system address instabilities introduced by the activated carbon filter. The suggested proportional controller has the potential to stabilize the control of CO<sub>2</sub> concentration, as well as making the calculation of photosynthesis and respiration rates more accurate. Advertised CO<sub>2</sub> concentrations of only 700 ppm aboard ISS will limit the maximum rate of photosynthesis sustainable within PGBA. The Atmosphere Control System has been tested for a typical 120 day tour of duty aboard ISS and can sustain plants autonomously without resupply or crew interaction. Full implementation of a proportional controller for CO<sub>2</sub> injection and scrubbing requires the identification of a suitable low power and low mass actuator, such as a gate valve, with adequate lifetime for ISS-type plant growth experiments.

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**DEFINITIONS, ACRONYMS, ABBREVIATIONS**

A/D Analog to Digital Converter.  
 ALS Advanced Life Support.  
 ATS Atmosphere Treatment System.

BaOH Barium Hydroxide.  
 CO<sub>2</sub> Carbon Dioxide.  
 DAC Data Acquisition and Control.  
 DIO Digital Input / Output.  
 H<sub>2</sub>O Water.  
 ISS International Space Station.  
 KSC NASA Kennedy Space Center.  
 L Liter.  
 LR Leakage Rate.  
 min Minute.  
 MLE Middeck Locker Equivalent, maximum internal dimensions are D20.320"xW17.337"xH9.969".  
 NASA National Aeronautics and Space Administration  
 NDS Nutrient Delivery System.  
 O<sub>2</sub> Oxygen.  
 P Pressure.  
 PAR photosynthetic active radiation (measured between 400-700 nm wavelength).  
 PGBA Plant Generic BioProcessing Apparatus.  
 PGC Plant Growth Chamber.  
 psi Pounds per Square Inch pressure.  
 PTIM Porous Tube Insert Module.  
 rH relative humidity.  
 SMAC Space Maximum Allowable Concentration.  
 STS Space Transportation System.  
 T Temperature.  
 TEC Thermoelectric Controller or Cooler.  
 UV ultraviolet.  
 VDC Volts Direct Current.  
 VOC Volatile Organic Compound.  
 WCSAR Wisconsin Center for Space Automation and Robotics, Madison, Wisconsin.