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Atmospheric Leakage and Condensate Production in NASA's Biomass Production Chamber. Effect of Diurnal Temperature Cycles

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ABSTRACT

A series of tests was conducted to monitor atmospheric leakage rate and condensate production in NASA's Biomass Production Chamber (BPC). Water was circulated through the 64 plant culture trays inside the chamber during the tests but no plants were present. Environmental conditions were set to a 12-hr photoperiod with either a matching 26°C (light) / 20°C (dark) thermoperiod, or a constant 23°C temperature. Leakage, as determined by carbon dioxide decay rates, averaged about 9.8% for the 26°C / 20°C regime and 7.3% for the constant 23°C regime. Increasing the temperature from 20°C to 26°C caused a temporary increase in pressure (up to 0.5 kPa) relative to ambient, while decreasing the temperature caused a temporary decrease in pressure of similar magnitude. Little pressure change was observed during transition between 23°C (light) and 23°C (dark). The lack of large pressure events under isothermal conditions may explain the lower leakage rate observed.

When only the plant support inserts were placed in the culture trays, condensate production averaged about 37 liters per day. Placing acrylic germination covers over the tops of culture trays reduced condensate production to about 7 liters per day. During both tests, condensate production from the lower air handling system was 60% to 70% greater than from the upper system, suggesting imbalances exist in chilled and hot water flows for the two air handling systems.

Results indicate that atmospheric leakage rates are sufficiently low to measure CO_2 exchange rates by plants and the accumulation of certain volatile contaminants (*e.g.*, ethylene). Control system changes are recommended in order to balance operational differences (*e.g.*, humidity and temperature) between the two halves of the chamber.

INTRODUCTION

With the capability to tightly seal the Biomass Production Chamber (BPC) at Kennedy Space Center, FL, unique measurements for large stands (20 m^2) of plants have been possible (Prince *et al.*, 1987). These measurements include plant stand CO_2 and O_2 exchange, transpiration of water, mineral uptake from nutrient solutions, and the accumulation of often undetected atmospheric contaminants. Detailed reports on the various components and subsystems of the BPC have been published elsewhere (Prince *et al.*, 1987; Sager *et al.*, 1988), as have results from preliminary biological tests and gas exchange rates (Wheeler *et al.*, 1990; Wheeler and Sager, 1990).

Past tests of the atmospheric seal integrity of the BPC have been conducted on a qualitative basis by searching for leakage points of helium or halon gas pumped into the chamber, and on a quantitative basis by tracking the decay rate of elevated levels of CO_2 (without plants in the chamber). Results from these tests have ranged from greater than 20% of the chamber volume per day early in chamber operation, to as low as 2% of the volume per day (J.H. Drese, unpublished; see also, Wheeler *et al.*, 1990). Major improvements in reducing the leakage rate resulted after the flexible air duct connectors were coated with a silicone sealant (RTV) and pneumatic seals were added to the chamber entry doors (Wheeler *et al.*, 1990).

Previous leakage tests have been conducted under isothermal conditions and thus not subjected to any pressure changes that might be encountered during a typical diurnal thermoperiod that might be used to grow crops. In this report, leakage rates were measured with a 26°C / 20°C diurnal thermoperiod (identical to conditions used to grow soybeans for crop tests) and compared to rates observed with constant 23°C (isothermal) conditions. The report also presents data on the production of condensate water from the chilled water coils of the heat exchange system during the leak tests. Results from this latter data set will provide an estimate of the upper limit of condensate water that can be attributed to direct evaporation, in comparison to transpiration (from leaves) during plant tests.

METHODS AND MATERIALS

Prior to starting the tests, the condensate tanks for the air handling systems were emptied and the carbon dioxide (CO_2) concentration inside the chamber was raised to about 2000 ppm. Tests lasted from approximately 30 to 60 hours and were conducted between the 2000 and 1500 ppm CO_2 range to minimize and effects of any variation in background CO_2 levels (Kimball, 1990). Doors were kept closed and pneumatic seals were activated for the duration of the testing. The chamber environment was set to the following conditions: a 12-hour light / 12-hour dark photoperiod (on 06:00 to 18:00, off 18:00 to 06:00), with either 26°C during the light and 20°C during the dark, or a constant 23°C (light and dark). Relative humidity ranged from 55% to 70% throughout the tests. Both environmental regimes match temperature conditions used from previous crop tests in the BPC with soybean (26°C / 20°C) and lettuce (constant 23°C). Throughout the tests, water was circulated continuously to the 64 plant culture trays inside the chamber (total tray area of approximately 16 m^2). Trays were either covered with white, acrylic "germination" covers (3 mm thick), or left uncovered with only the plant support inserts (see Prince and Knott, 1989) positioned inside each tray. Nutrient solution return gutters were completely covered for both tests. Typically, germination covers are used during the first 2 to 5 days of plant tests, after which, only the plant support inserts and plant shoots cover the base of the trays.

Measurements. Carbon dioxide concentrations were monitored continuously using Anarad (Santa Barbara, CA) model 203 infrared gas analyzers (IRGAs), with all sample gas streams being returned to the main chamber. IRGAs were calibrated with a "zero" (N_2) and 1010 ppm span gas before and after the test and the appropriate corrections added to the leak calculation. All gas analyzers are guaranteed accurate to $\pm$ 1% full scale ($\pm$ 25 ppm). Atmospheric leakage rates were calculated using the approach of Sager *et al.*, 1988 (see also, Acock and Acock, 1989) and assumed a chamber volume of 112.6 m^3 (Sager *et al.*, 1988). When trays were left uncovered, condensate tanks from the lower and upper air

handling systems were emptied at 12-hr intervals (06:00 and 18:00 each day) and volumes recorded. For tests when trays were covered with the plant "germination" covers, tanks were emptied only at the end of the experiment.

RESULTS AND DISCUSSION

Atmospheric leakage rate. Hourly averages of CO_2 concentration and atmospheric pressure during a leak test in the BPC are shown in Fig. 1. As might be expected in a tightly sealed system with a fixed volume, atmospheric pressure changes occurred in conjunction with temperature changes (Barrante, 1977). Warming caused a positive pressure event, while cooling caused a negative pressure event. When chamber temperatures were held constant, only a small pressure event was observed, which likely reflects adjustments by the heat exchange system in response to the lamps being turned on or off. In all cases, chamber pressures eventually equilibrated with ambient, suggesting that mass exchange (leakage) had occurred.

Two hours prior to the 26°C cycle, CO_2 concentration equaled 1898 ppm (Fig. 1); after 24 hours, CO_2 concentration had decreased to 1754 ppm (2 hrs prior to the 23°C light cycle). Assuming the leakage occurs in a logarithmic fashion against an external gradient of 350 ppm, the average leak rate (L) for cycling thermoperiod would then equal:

$$L = \frac{1}{(t_2 - t_1)} \times \ln\left[\frac{C_1 - C_{amb}}{C_2 - C_{amb}}\right]$$

$$= \frac{1}{24\ hr} \times \ln\left[\frac{1898 - 350}{1754 - 350}\right]$$

$$= \frac{1}{24\ hr} \times \ln\left[\frac{1548}{1404}\right] = \frac{0.098}{24\ hr}$$

= 9.8% of chamber volume per day

(for the 26°C / 20°C thermoperiod)

Two hours after the beginning of the 23°C light phase, CO_2 concentration equaled 1752 (Fig. 1); after 24 hours, CO_2 concentration had decreased to 1653 ppm. In this case, leakage rate (L) would then equal:

$$L = \frac{1}{24\ hr} \times \ln\left[\frac{1752 - 350}{1653 - 350}\right]$$

$$= \frac{1}{24\ hr} \times \ln\left[\frac{1402}{1303}\right] = \frac{0.073}{24\ hr}$$

= 7.3% of chamber volume per day

(for constant 23°C temperature)

These results suggest that leakage from the BPC is slightly higher with a diurnal thermoperiod in comparison to isothermal conditions--about 1.5% in this case. Using Gay-Lussac's Law (Charles' Law) relating absolute temperatures and volumes for ideal gases (Barrante, 1977), the change in volume (*i.e.*, leakage after the pressure difference has returned to near zero) resulting from the temperature change can be estimated, where:

$$V_1 / T_1 = V_2 / T_2 \text{ or } V_2 = (V_1 T_2) / T_1$$

(where V_1 and V_2 and T_1 and T_2 equal the volumes and temperatures in °K at times 1 and 2)

Then for the BPC (see Sager *et al.*, 1988):

$$V_2 = (112.6\ m^3)\ (299°K) / (293°K)$$

$$V_2 = 114.9\ m^3$$

The amount leaked would then = $V_2 - V_1$

= 114.9 m^3 - 112.6 m^3 = 2.3 m^3

This is equivalent to about 2% of the BPC volume being leaked just from a 6°C temperature change each day, and this closely matches the 1.5% difference observed between the cycling thermoperiod and isothermal conditions tested. It is interesting to note that during the positive pressure event (*e.g.*, from 6°C warming; Fig. 1), a volume of about 2.3 m^3 would have leaked "outward", while during a negative pressure event, about 2.3 m^3 would be drawn into the chamber. This would result in a net exchange of 2.3 m^3 during each 24-hr cycle. One would expect to see a noticeable drop in CO_2 concentrations after a cooling event as a result of the dilution from incoming 350 ppm CO_2 gas (*i.e.*, air around the chamber), and such a drop appears in Fig. 1. However, an apparent increase in CO_2 also can be seen when going from 20°C to 26°C, creating a "square-wave" pattern of CO_2 concentration in response to temperature. This suggests that there may be some persisting pressure effects on the IRGAs (*e.g.*, changes in gas return line back pressure), and direct pressure measurements should be taken close to the IRGAs to confirm this. Assuming the gas stream in the IRGAs was at a constant temperature, the density of CO_2 in the analyzers would then be directly proportional to pressure (Jarvis and Sandford, 1985). Thus a pressure change of 320 Pa (Fig. 1) would change the density of the gas in the IRGA by approximately (320 Pa/101300 Pa), or 0.32%. At a concentration of 1700 ppm, this would result in an apparent 5.4 ppm change in concentration, which in turn could change leakage calculations by 0.4% for a 24-hr period.

Another potential source of error would be loss of CO_2 in the condensate water produced on the cold coils; however, with a solubility of 0.88 ml CO_2 per ml of H_2O below an atmosphere of pure CO_2 at 20°C (Forsythe, 1969), at 1700 ppm (average) CO_2 concentration, the chamber would then lose 0.88 x 0.0017 = 0.0015 ml CO_2 per ml H_2O. If 37 liters of condensate were lost per day (Table 1), then (0.0015 ml CO_2 per ml H_2O) x (37,000 ml H_2O per day), or 55.5 ml CO_2 would be lost per day. This would amount to 0.055 liters / 112,600 liters, or 0.5 ppm CO_2 loss from the chamber, which would be insignificant with regard to the leakage test.

A comparison of leakage rates during the middle portions (*i.e.*, avoiding transition period) of the 26°C (light) and 20°C (dark) cycles showed that leakage was slightly higher during the 26°C period (9.5% vs. 8.0%) (Fig. 1); however, a second test (data not shown) showed little difference and further measurements would be needed to compare rates at different temperatures.

It should be noted that the analyzers used to monitor CO_2 were accurate to only $\pm$ 1% full scale and readings were subject to fluctuations from small pressure events (typically < 50 Pa) as a result of temperature control within the system (Fig. 1). Thus there is a degree of imprecision in the leakage estimates. In practice, however, the error can be minimized by 1) using long-term data sets (we typically used 24 to 72-hr tests), 2) avoiding readings during changing pressure, and 3) correcting for any zero or gain drift after the experiment (Sager *et al.*, 1988). The fact that both the 9.8% and 7.3% daily leakage rates approximately match values determined in February and May of 1990 (J.H. Drese, unpublished) and the 5% to 10% leakage rates determined over the past two years (Wheeler *et al.*, 1990) adds a degree of confidence to these estimates. In addition, the findings confirm that no major changes occurred with regard to system closure over the past two years.

Condensate. Condensate production rates from the chamber (when no tray covers were used) are shown in Table 1. Despite differences in temperature, condensate production from the chamber remained close to **37 liters per day**. When acrylic germination covers were placed over the trays and the series of temperature/light treatments was repeated, condensate production for the entire test (65 hrs) was reduced to 20.6 liters, or **7.6 liters per day**. This indicates that direct evaporation was indeed responsible for the condensate production (as opposed to residual water in the air ducting or a leak in the heat exchange coils). Interestingly, even with tray covers present, some water can still evaporate from the trays, indicating that the covers are not perfect seals.

The rates of condensate production from the uncovered trays in an empty chamber were somewhat higher than expected, based on the amount of directly exposed water surface in the chamber. Exposed water surfaces were limited to gaps (approximately 2 to 4 mm wide) along the edges of the tray inserts and any uncovered portions of the plant support strips (Prince and Knott, 1989). In addition, the water level was recessed from 3 to 4 cm below these gaps in the tray inserts. Another potential source of water would be from air in the headspaces above the nutrient solution tanks, which are atmospherically connected (closed) to the chamber by a 5.7-cm PVC pipe. However the headspace volumes represent less than 0.3% of the chamber volume and air exchange rates were considered to minimal.

Condensate production with full plant stands can reach 100 to 150 liters day^{-1} for the entire chamber, depending on environmental conditions (Wheeler *et al.*, 1990). It has been assumed that most of this was due to plant transpiration, but results from the tests reported here suggest that this may not be true, particularly early in growth when the plant canopy is incomplete. It is likely, however, that the contribution from direct evaporation of nutrient solution decreases during plant experiments as the stems and leaves begin to 1) shade the tray tops, thereby decreasing direct radiation of the trays, and 2) decrease air circulation at the surface of the trays. The latter would create a boundary (stagnant) layer at the tray top, thereby reducing the humidity gradient immediately above exposed areas of water. However, both of these tenets remain to be tested.

Vapor pressure deficits (difference between ambient water vapor pressure and saturated water vapor pressure) ranged from 7 to 13 mb, and averaged 10 mb for the sequence of 26°C / 20°C and constant 23°C regimes. In a repeat test using only 26°C / 20°C treatments but with slightly higher humidities (average vapor pressure deficit of 9 mb), condensate production averaged about 30 liters per day, pointing out the strong influence of vapor pressure deficit on evaporation rates in the chamber.

As seen in past measurements, more condensate water is generally produced from the lower air handling system, suggesting that the heat exchange systems for the two air handlers are working differently (*e.g.* different amounts of hot and chilled water flows between the upper and lower exchangers). The higher rates of condensate production from the lower chamber have also been noted during plant tests (C. Mackowiak and L. Siegriest, unpublished). Ultimately, this should be detectable as differences in absolute humidity between the upper and lower systems.

RECOMMENDATIONS

With the addition of pneumatic door seals, atmospheric leakage rates in the BPC have remained relatively constant (5% to 10%) over the past two years (1989 through 1990; J.H. Drese, unpublished; Wheeler *et al.*, 1990). Further improvements will likely require major changes to the physical system, *e.g.*, improvement of seals around blower shafts or elimination of atmospheric pressure transients that occur during temperature changes. Control of pressure events could be achieved by only conducting isothermal experiments, but this would be restrictive regarding the crop physiology. Alternative pressure controls might include: 1) allowing system volume changes to avoid pressure changes (*e.g.* addition of a bladder or bellows system; Hand, 1973), or 2) addition of an active system to compress gas during positive pressure events and release compressed gas during negative events (J.C. Sager, unpublished). The second approach would maintain a fixed volume but effectively partition pressures (and mass) within the system and is currently under design for installation to the BPC (J.C. Sager, unpublished).

Regardless of further improvements in leakage rate for the BPC, the current system performance is more than adequate for calculations of plant stand CO_2 exchange rates, which typically can be measured from 1-hour data sets. The typical error due to leakage over 1 hour would amount to 8% day^{-1} / 24 hrs day^{-1}, or 0.3% $hour^{-1}$ and thus can be ignored for short-term measurements (Wheeler, 1990). Whether the 5% to 10% leakage is

acceptable with regard to studying accumulation of low-level contaminants remains to be tested. Results to date with wheat, lettuce, and soybean crops have shown that closure is sufficient to cause ethylene gas produced by the plants to accumulate to levels greater than 100 X ambient levels (B. Vieux unpublished; Wheeler *et al.* 1990).

Humidity control discrepencies between the two chambers should be resolved in order to conduct more precise analyses of the water fluxes. Chilled water flow rates to the heat exchangers should be balanced between the upper and lower systems (differences currently exist) and new control algorithms (PID statements) might be tested. To date, supplementary humidification (other than from the plant transpiration) has often been deactiviated during crop tests to facilitate water budget keeping, and this has impeded more accurate humidity control. If additions of water for supplemental humidification can be monitored accurately, humidifiers could be activated throughout plant tests.

Further testing will be required to precisely define the amounts of water coming from direct evaporation versus leaf transpiration with actively growing plant stands. However, this remains an academic question with regard to system performance since the combined evaporation of water, regardless of the origin, is directly measureable as condensate. One possible approach to separating the two would be to measure condensate production with and without surrogate (non-transpiring) plants, which could create a similar shading and boundary layer effect at the tray surface.

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Table 1. Water condensed from the heat exchange systems of the Biomass Production Chamber while nutrient solution was circulated through culture trays without plants. Plant support inserts were present but no germination covers were used (see text).*

Date/Time	Conditions for prior 12 hours	Upper** System	Lower** System	Chamber Total	Daily Production
		(liters)	*(liters)*	*(liters)*	*(liters/day)*
11/16 06:00	dark/20°C	---Condensate tanks emptied---			
11/16 18:00	light/26°C	6.0	13.0	19.0	
					37.3
11/17 06:00	dark/20°C	7.1	11.2	18.3	
11/17 18:00	light/23°C	7.3	11.5	18.8	
					37.2
11/18 06:00	dark/23°C	6.6	11.8	18.4	

* *Relative humidity ranged from 60% and 75% during testing.*
** *Refers to upper or lower air handling systems used for air circulation and temperature and humidity control.*

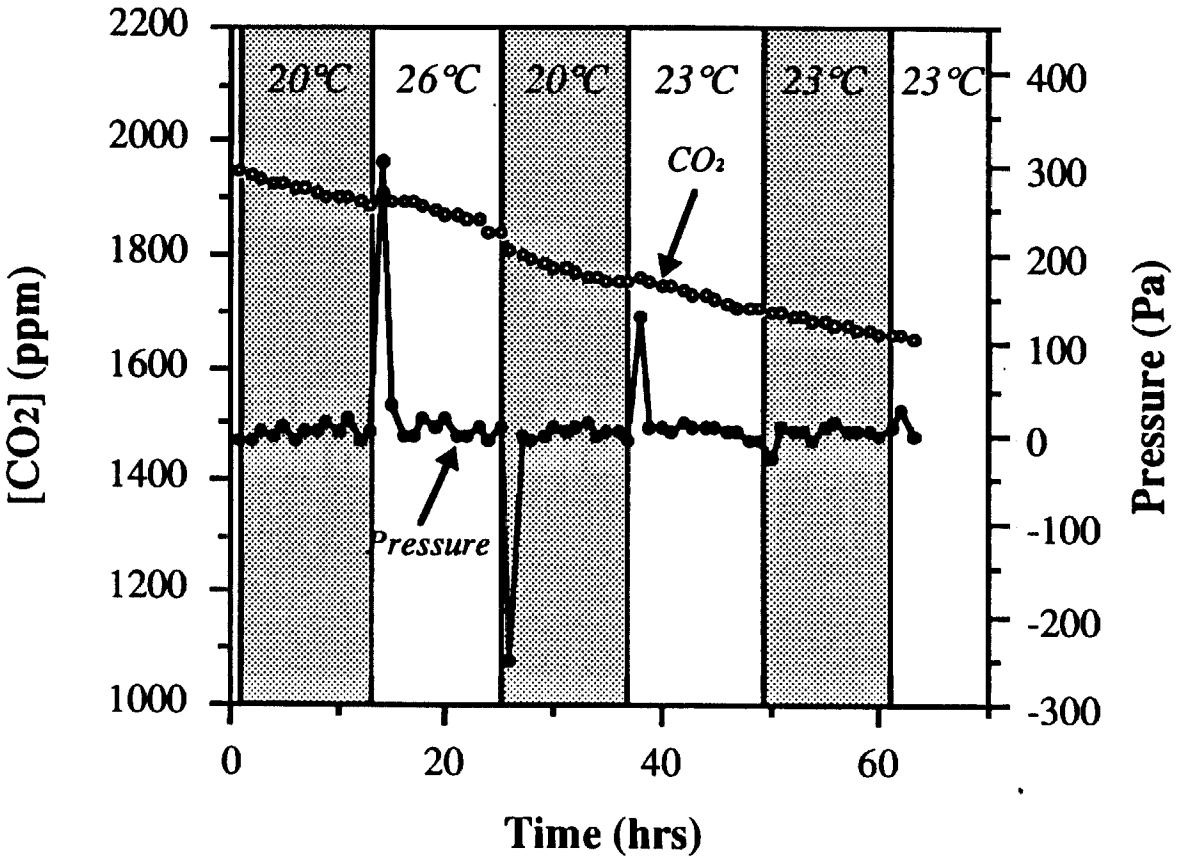

Figure 1. Effect of temperature on atmospheric pressure and leakage rate of CO_2 gas from the Biomass Production Chamber.

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15. Supplementary Notes

16. Abstract

Tests were conducted in NASA's Biomass Production Chamber (BPC) to monitor atmospheric leakage rate and condensate production from direct evaporation. Water was circulated through the plant culture trays during the test but no plants were present. Environmental conditions were set to a 12-h photoperiod with either a matching 26°C (light) / 20°C (dark) thermoperiod, or a constant 23°C temperature. Leakage, as determined by CO_2 decay rates, averaged 9.8% for the 26°/20° regime and 7.3% for the constant 23° regime. The higher leakage during the cycling temperature regime was attributed to pressure changes (up to 0.5 kPa) which resulted from the temperature changes. Condensate production (from direct evaporation) averaged 37 liters per day. Placing acrylic covers over the trays reduced this to about 7 liters per day. Results suggest that leakage is sufficiently low to measure CO_2 exchange rates by the plants and that direct evaporation can contribute significantly to condensate production from the air handling system, particularly early in plant growth when tray tops are not covered by leaves.

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