NASA Technical Memorandum 103494

System Development And Early Biological Tests In NASA's Biomass Production Chamber

March 1990

National Aeronautics and
Space Administration

NASA Technical Memorandum 103494

System Development And Early Biological Tests In NASA's Biomass Production Chamber

R. M. Wheeler, C.L. Mackowiak, T. W. Dreschel, J.C. Sager,
R. P. Prince, W. M. Knott, C. R. Hinkle, and R. F. Strayer
The Bionetics Corporation
Kennedy Space Center, Florida 32899

March 1990

National Aeronautics and
Space Administration

John F. Kennedy Space Center

NASA

INTRODUCTION

With the continuing commitment by NASA's CELSS (Controlled Ecological Life Support System) Program to develop and evaluate a bioregenerative life support system, a need arose to construct a large test module for studying plant growth in an atmospherically sealed system. Construction of such a module, the Biomass Production Chamber or BPC, began at Kennedy Space Center, FL in the spring of 1985. Although heavy construction relating to the chamber air handling system, electric lighting, and plant growing racks was completed by the spring of 1987, system upgrades and modifications of both the physical components and computer control software have continued to the present. Over a four-year period, five crops of wheat have been grown.

This report summarizes the chamber's physical system evolution and gives a brief summary of the biological (crop) test results for the past four years. Methods and procedures for the biological tests and more detailed discussions of yields are presented near the beginning of the RESULTS AND DISCUSSION section (see PHASE II section below). In depth discussions of the chamber's current and proposed capabilities can be found in Prince et al. (1987) and Sager et al. (1988), and a detailed report of biological test results is currently in draft as a separate report (Corey et al. unpublished).

The Biomass Production Chamber at Kennedy Space Center provides the first closed biomass production facility for NASA's CELSS program. Because of the visibility of the project, it was used as soon as possible. The ongoing instrumentation and cul-

tural augmentation resulted in all of these tests being influenced in some way with experimental disturbances such as opening of the doors, lighting of the plants during dark cycles, and cutting short or extending the growing cycles. Work schedules also influenced to some extent the choice of day/night cycles, growing days, and the amount of closure that could be maintained. By far the most frequent disturbances related to equipment and sensor failures. As pointed out in Table 1, many of the control equipment and sensors, and chamber seals were not in place during early phases of testing. In addition, calibration of sensors often had to be performed during biological tests. Changes continue to be made in the control system program and monitoring sensors and techniques.

How much any one or all of a number of these uncontrollable events affected plant growth cannot be determined. Certainly, chamber environmental control capabilities improved from Phase I to Phase V. Mechanical failures received priority and, unfortunately, not as many resources were available for improving culture practice for the crops.

This report describes the progression of chamber development from January 1985 to November 1989 (Table 1). For the sake of simplicity, the developmental time line has been divided into five phases to coincide with the biological tests which are listed separately in Table 2.

RESULTS AND DISCUSSION

PHASE I (Jan 1985 - Aug 1987)

Physical System

During Phase I, light construction activities of the chamber continued and only the upper portion (two shelves) of the chamber was available for growing plants. Carbon dioxide enrichment and control were not available and no capabilities were in place to monitor trace contaminants (e.g. gaseous hydrocarbons); consequently, the chamber was operated in an open mode throughout testing (i.e. fresh air exchange was provided). Full temperature control and dehumidification capabilities were in place, but no supplementary humidification could be provided. Lamp dimming capabilites (using the "Wide-Lite" high pressure sodium ballasts) were also in place but had not yet been tested. Temporary nutrient solution reservoirs were positioned outside and adjacent to the lower chamber door. Solution pH and electrical conductivity (nutrient replenishment) were controlled manually.

Biological Test (Dec 1986 - April 1987)

The initial biological test in the BPC was undertaken primarily as a systems operation check. Consequently, complete growth data were not kept and harvest data were not considered reliable. On the basis of studies conducted at Utah State University, 'Yecora Rojo' wheat (Triticum aestivum L.) was chosen for the test (Bugbee and Salisbury, 1988; Salisbury and Bugbee, 1988). Seeds were sown at a rate of 800 m^{-2} (200 per 0.25 m^2 tray) on to specially designed tray inserts to support the germinating plants about 5 cm above a continuous flowing nutrient

film (Prince and Knott, 1989). Translucent white acrylic covers were placed over the trays to maintain high humidity during germination. Each of the two shelves in the upper portion of the chamber could support 16 trays, for a total of 32 trays (Prince et al., 1987). Two trays were sequentially planted at 4-day intervals to set up a repetitive plant/harvest cycle. Qualitative observations showed that wheat plants could be germinated and grown to full maturity in approximately 65 to 75 days with a single, replenished nutrient solution. In addition, shoot heights could be confined to the available 60 cm of vertical growing dimension between the culture trays and lamp barriers.

PHASE II (Aug 1987 - Aug 1988)

Physical System

As with Phase I, Phase II testing was conducted only in the upper portion of the chamber using the levels (shelves) 1 and 2 (Table 1). In addition to complete temperature and dehumification control, CO_2 concentrations could be monitored and controlled using infrared gas analyzers and the main programable logic controller (PLC) (Sager et al., 1988). With the addition of CO_2 control, the doors could be kept closed as much as possible. During periods of closure, leakage rate from the chamber (as determined by CO_2 decay rate tests) ranged from 20 to 40% of the total volume per day, or approximately 1 to 2% per hour (Table 1). Tests conducted by adding either helium or halon gas to the chamber showed the main leakage points to be around the two chamber doors and the fan shafts for both the upper and lower air handling systems. For Phase II testing, nutrient solutions were

recirculated from large (300-liter) PVC reservoirs permanently mounted outside the chamber on the ground floor. Nutrient solution pH was controlled to between 5.8 and 6.2 by adding dilute nitric acid with portable, automatic controllers placed inside the chamber. All components of the nutrient delivery system were sealed and all air spaces vented back to the chamber.

Biological Test (May 1988 - Aug 1988)

Growing procedures. The second planting again used 'Yecora Rojo' wheat sown at 1600 seeds per m^{-2}. In contrast to the previous test, all 16 trays of level 2 (the lower of the two shelves) were planted at one time. Fifteen days later, all 16 trays of level 1 were planted. A 24-hr photoperiod (i.e. continuous light) was maintained with full lamp intensity throughout the entire growth cycle, providing an average photosynthetic photon flux (PPF) of 660 umol m^{-2} s^{-1}, or 57 mol m^{-2} day^{-1}. Air temperature and relative humidity were held constant at 23°C and 65%, respectively, while the CO_2 concentration was maintained at 1000 ppm (Table 1). For all biological tests (except where noted), a complete nutrient solution roughly similar to a 1/2 strength Hoagland solution was used (Marschner, 1986). Modifications of the solution for wheat studies were based on previous tests conducted at KSC (Mackowiak et al., 1990) and from information reported in the literature (Bugbee and Salisbury, 1988; Salisbury and Bugbee, 1988). In all cases, nitrogen was supplied only as nitrate salts and except for Phase I, iron was provided as an EDTA-chelate (Mackowiak et al., 1990).

Harvest results. Trays from level 2 were harvested sequentially at 68, 74, 80, and 86 days after planting (four trays per harvest; Table 2). Trays from level 1 were harvested at 68, 70, 72, and 73 days after planting. (Level 1 harvests were advanced to accommodate scheduled physical modifications to the chamber). A total of 23.07 kg of plant biomass was produced from the different harvests with 9.25 kg of that total being seed (harvest index of 40%). Assuming approximately 8 m^2 of growing area (32 0.25-m^2 trays), and an average cycle of 74 days, then crop growth rate would equal 39.0 g m^{-2} day^{-1} for total biomass and 15.6 g m^{-2} day^{-1} for seed. The four best trays from the study (two harvested at 72 days and two at 74 days) averaged 908 g total biomass and 391 g of seed for a harvest index of 43%. Thus the best crop growth rates achieved (in this case using 72 days) equaled 50.4 g m^{-2} day^{-1} for total biomass and 21.7 g m^{-2} day^{-1} for seed.

Proximate nutritional analyses (conducted by Nutrition International, Inc., East Brunswick, NJ) of the harvested tissue showed that dried seed averaged 18.9% protein, 3.2% fat, 72.9% carbohydrate, and 2.5% crude fiber, with a calculated nutritional energy content of 3.96 kcal g^{-1}. Straw tissue (leaves and stems) averaged 14.4% protein, 2.5% fat, 39.5% carbohydrate, and 27.7% crude fiber.

Yields and seed set from Phase II testing were the best of any tests yet conducted in the BPC (Table 2). A comparison of total biomass from the trays harvested with measured wheat yields under optimal conditions (Bugbee and Salisbury, 1988; their Fig. 8) for a similar irradiance shows that the BPC yields fell about

40% below yields under more optimal conditions. A comparison of the best trays, however, shows only 20% below optimal yields. This suggests that near optimal yields with wheat should be achievable on a large scale with moderate atmospheric closure.

Air temperatures and CO_2 concentrations for the Phase II test were within reported optimal ranges (Salisbury and Bugbee, 1988); thus the less than optimal yield (for 51.5 mol m^{-2} day^{-1} PPF) could have been related to limitations in the root zone environment. These might include mild deficiencies or imbalances in the nutrient solution, possible nutrient solution contaminants, root-zone pathogens, or differences in cultural practices affecting water and mineral uptake by the plants. To date, BPC studies have utilized nutrient film technique (Graves, 1983), while the highest yields for wheat have been reported from systems using a rapid-flowing deep solution culture (Bugbee and Salisbury, 1988, 1989). This latter approach may provide a more optimal root environment, particularly under conditions favoring rapid growth, e.g. high irradiance (Bugbee and Salisbury, 1989; Chung et al., 1989).

Throughout all testing in the BPC, nutrient levels in solutions were analyzed on a weekly or biweekly basis. In addition, solution microflora (bacteria and fungi) counts were conducted at regular intervals (Table 2), but no specific analyses or assays were conducted for plant pathogens. During Phase IV and V, plant tissue samples also were taken at weekly intervals throughout growth and sent to Dr. Wade Berry of UCLA for elemental analysis (Table 2).

Environmental measurements. At weekly intervals throughout growth, extensive data were gathered on irradiance (PPF), air velocity, and plant canopy (infrared) temperature. Results showed that PPF varied significantly depending on tray position; for example, PPF levels over end trays were typically 25 to 35% lower than centrally located trays. This in part may explain the large variation in yield between trays (Table 2). In addition, PPF varied from the front (inner edge of the circular tray arrangement; see Prince et al., 1987) to the back (outside edge) of individual trays, and these differences steepened as plant shoots grew closer to the lamps. Air velocities as measured with a hot wire anemometer typically ranged from 0.2 to 1.2 m s^{-1}, while infrared temperatures of plant shoots typically stayed within $\pm$ 1°C of the surrounding air temperature. These findings suggest air movement within the chamber was adequate to provide good mixing (Krizek, 1978). Whether the higher air velocities may be imposing some desiccation or mechanical stresses will require further study (Mitchell et al., 1975). Spot samples of the chamber atmosphere for ozone showed the chamber air did not differ significantly from air outside the chamber, with levels ranging from 40 to 60 ppb (J. Drese, unpublished).

Because the chamber was reasonably well sealed (20-40% leakage per day) and temperature and relative humidity were held constant throughout growth (23°C and 65%), water condensed from the air handling heat exchangers closely represented transpiration from the wheat stand. As shown in Table 2, 3615 liters of water were condensed from the chamber atmosphere, or about 6.1 liters m^{-2} day^{-1} over the average 74-day growth cycle (Table 2).

In comparison, a total of 3914 liters of water was added to the nutrient solution systems. The slightly greater volume of added water likely reflects losses from several plumbing leaks during the test. Throughout growth, a total of 1868 ml of concentrated nitric acid (15.7 M) was required to maintain pH in the two nutrient delivery systems, or 3.1 ml of acid m^{-2} day^{-1}. It is important to note that nitrate-nitrogen (usually 7.5 mM) was used for the nutrient solution in all the studies reported, thus pH control always required addition of acid (Marschner, 1986).

PHASE III (Aug 1988 - Jan 1989)

Physical System

System components and capabilities remained relatively unchanged from Phase II with the exception of completion of computer controls for the lower chamber nutrient delivery systems (levels 3 and 4) and the degree of atmospheric closure for the entire chamber. The original rubber gaskets sealing both doors to the chamber were replaced with pneumatic (inflatable) gaskets to reduce leakage. In addition, insulation was stripped from all the air handling system ducts to coat all the flexible connecting sleeves with a silicone (RTV) sealant. This included 64, 20-cm diameter penetrations into the main chamber, 16, 41-cm main duct connections at the back of the chamber, 4, 56-cm connections to a delivery plenum after the blowers, 4, 56-cm connections on the main air return lines and various sample ports and access panels. In addition, access doors to the coarse and HEPA filter housings for both air handlings systems were totally sealed with the RTV compound. Carbon dioxide (CO_2) concentration decay tests after

sealing the air handling system showed that leakage rates were reduced to about 10 to 20% of the volume per day, or just slightly less than 1% per hour.

Lamp dimming tests were conducted to monitor changes in total photon flux and shifts in spectral quality as a function of power to the lamps. Results showed near maximum output from the lamps could be sustained from 100% down to 70% power, but below about 60% power, lamp output dropped sharply. At a dimmed setting of 30% (the lowest level for dimming), lamp output was only 10% of maximum. In addition to the drop in total irradiance, lamp spectral quality changed gradually with dimming: At the maximum dimmed level (30% power), most of the output in the photosynthetically active band was restricted to a peak near 589 nm, with a smaller peak near 570 nm (as measured with a LI-COR Li-1800 spectroradiometer). Another peak near 819 nm in the farred region also persisted at maximum dimming. Thus the spectral output at the lowest setting was somewhat similar to that of a low pressure sodium lamp (Sager et al., 1982) and basically agrees with findings reported by Bingham and Coyne (1979). The tests with the BPC dimming system also showed that the eight lamp banks (as controlled by the computer) and the individual lamps and ballasts showed a high degree of variability in their dimming response.

Biological Test (Nov 1988 - Jan 1989)

Wheat again was planted for the third phase test, but this time all four growing levels and nutrient delivery systems were used. This was the first test of the catchment, or sump tank and

volume modulating controls needed for the level 4 nutrient delivery system (Prince et al., 1987). A total of 44 of the possible 64 tray positions were planted for the test (11 trays per growing level). Tray positions were randomly assigned using a balanced incomplete block design (Sokal and Rohlf, 1981) for a comparison of position effects within the chamber. Nutrient solution pH and conductivity were controlled manually each day. Because of facility scheduling, the crop was not carried to full maturity and seed yield data were not collected (Table 2).

In contrast to the previous crop tests with continuous lighting, a 20/04 (L/D) photoperiod was used with a matching 20° C/16°C thermoperiod. As before, CO_2 level was controlled to 1000 ppm by injecting a small amount of pure CO_2 during the light cycle (to compensate for photosynthetic uptake by the plants). However, with a daily dark cycle and the chamber being more tightly sealed than in the past, CO_2 tended to rise from plant respiration during the dark when photosynthesis was not active. For the first 25 days of the study, build-up of CO_2 in the dark cycle was controlled by injecting compressed CO_2-free "breathing air" (approximately 79% N_2 and 21% O_2) to maintain the 1000 ppm set point. At 25 days after planting, the breathing air supply temporarily ran out resulting in a linear increase of CO_2 during the dark period. At this point, it was decided to abandon further attempts to suppress CO_2 increase during the dark cycle and monitor the nightly increase and subsequent drawdown back to 1000 ppm each day when the lights were turned on. This was the first effective demonstration of the BPC as a closed gas exchange system to track plant stand photosynthesis and respiration (Coombs

et al., 1985). As with Phase II, spot samples for ozone showed no substantial difference between atmospheres inside and outside the chamber (J. Drese, unpublished).

PHASE IV (Jan 1989 - May 1989)

Physical System

Supplementary humidification capabilities were added to the chamber during Phase IV. This consisted of a nozzle on a deionized water line placed inside the main ducts of the upper and lower air handling systems. When humidification was required (typically only during the first two weeks of growth), the control computer would open a solenoid valve in the water line to allow a water spray into the air stream. In an attempt to provide a better gas seal around the fan shafts, a deionized water line was plumbed to each blower unit permitting a small amount water to drop onto the shaft just adjacent to the seal and bearings on the fan housing (about one drop every 5 to 20 seconds). This provided a continuous water seal in the bearings and reduced leakage rates from the chamber to about 5-10% per day.

Computer (PLC) control statements and hardware for nutrient solution pH and electrical conductivity were added and tested (Prince et al., 1987). Initial design plans for conductivity control involved four separate stock solution reservoirs with a fifth reservoir containing deionized water. The four stock reservoirs would allow concentrated solutions of different salts to be kept with minimal risk of precipitation. Upon demand, a portion of each stock solution would be added to one of the main

nutrient solution systems, with deionized water added to rinse the plumbing between each stock. However, to simplify mineral budget keeping, it was decided to a use single, complete stock solution (i.e. containing all the essential nutrients) for each nutrient delivery system. This eliminated the need for a water rinse after each addition and also allowed direct tracking of nutrients added to each system. Preliminary tests with complete stock solutions (with concentrations up to 18.0 dS m^{-1} EC) showed no detectable precipitation over seven days.

Biological Test (Jan 1989 - May 1989)

For the Phase IV test, all 64 trays positions in the BPC were planted with 'Yecora Rojo' wheat. This provided about 16 m^2 of area with the growing trays. (Note: this does not account for gaps between trays and the tendency of shoots to lean along the edges). Pneumatic door seals were activated as often as possible to maintain tight atmospheric closure throughout growth. On several occasions during the study, nutrient solution pumps and lamps were turned off for the number 4 level because of low water level alarms from the sump tank. The alarms always occurred during a transition from light to dark when the chamber temperature was lowered from 20° to 16°C. It was later determined that an atmospheric suction equivalent to 100 to 120 mm of water (about 1 kPa) was occurring inside the chamber during the change from day to night conditions. Because the nutrient solution tanks were vented to the main chamber, pressure transducers used to monitor the levels would incorrectly sense a 10 to 12 cm drop in the reservoir and place the system into alarm. To circumvent

this, a float switch and a differential pressure transducer (vented to the chamber atmosphere) were added to the sump tank. It is interesting to note that water condensed from the chamber during the study exceeded the amount added to the nutrient solution tanks (Table 2). This was likely a result of residual water in the air handling system from supplementary humidification during the first 2 weeks of plant growth.

Using the CO_2 rise during the dark and the subsequent drawdown when the lamps turned on each day, a complete set of stand gas exchange data was gathered. A detailed report of this is in preparation (Wheeler and Sager, In Press). The results showed that: 1) stand photosynthesis peaked near 25 days after planting and then gradually declined with age; 2) photosynthesis increased linearly with irradiance (750 umol m^{-2} s^{-1} PPF maximum tested) with a light compensation point near 200 umol m^{-2} s^{-1}; 3) photosynthesis decreased sharply when CO_2 dropped below approximately 700 ppm and did not increase much above 1000 ppm; 4) dark period respiration was nearly 75% greater at 24°C compared to 16°C; and 5) after reaching full vegetative ground cover, water transpiration rate remained relatively constant throughout growth.

Despite the encouraging gas exchange data, final harvest results were disappointing with regard to potential yields (Bugbee and Salisbury, 1988). Total biomass averaged only 55% of reported optimal yields (65% for the four best trays) for an irradiance of 38 mol m^{-2} day^{-1} (530 umol m^{-2} s^{-1} for 20 h/day). Harvest index averaged 29% (31% for the 4 best trays) in comparison to a more typical ratio of 45% obtained in studies at

Utah State (Bugbee and Salisbury, 1988; Salisbury and Bugbee, 1988). This would suggest that the problems were related to poor seed set. Nutrient solution and tissue analyses showed that copper levels were low, and copper deficiencies are known to reduce seed set (Marschner, 1986). Discussion of tissue analysis results with Dr. Wade Berry of UCLA showed no other serious deficiencies and no toxicities. Nitrogen levels were not analyzed, but subsequent tests under similar conditions comparing growth at 7.5 mM (used in the BPC) with 15.0 mM showed no obvious improvements (C.L. Mackowiak, unpublished).

In conjunction with the poor yields, for the first time in any BPC test, flag leaves of the wheat plants showed an epinastic rolling along the longitudinal axis. This symptom recurred along with poor seed set during the Phase V test and both are discussed further below.

PHASE V (May 1989 - Nov 1989)

Physical System

With the exception of nutrient solution temperature and suppression of CO_2 buildup, full environmental control was available for Phase V testing (Table 1). However, a temporary failure of the hot water pump for the lower air handling system caused poor temperature control during the dark period for the first 10 days of biological test. During this time, the lower chamber tended to overshoot the desired night temperature set point of 16°C, often reaching 13° or 12°C for approximately one hour immediately after the lamps were turned off. In an attempt to increase irradiance at the tray level, white, ABS plastic reflector panels were suspended just beneath the lamp canopy at the ends of each

growing level. This raised tray-level PPF by 10-15% for the end positions, and approximately 5% for the second position in from the ends. Use of water to seal the air handling fan shafts was discontinued for Phase V. Instead, the space between the fan housing and the first support bearing (pillow block) was capped with RTV sealant. Carbon dioxide concentration decay tests conducted prior to the biological test showed that leakage rates were less than 10% of the chamber volume per day (less than 0.5% per hour), and tests conducted after the biological test showed leakage rates of less than 5% day with the chamber internal pressure maintained near atmospheric (less than 0.2% per hour). Mass flow meters and signal integrators to monitor the amount of CO_2 added to the chamber were calibrated and brought on-line.

Biological Test (May 1989 - Aug 1989)

To increase germination uniformity, 5-cm wide strips of hydrophyllic Nytex plastic were placed in seed holding slots of each tray insert (Prince and Knott, 1989; Mackowiak et al., 1990). Based on nutrient solution and tissue analyses from the Phase IV test, copper and zinc levels were raised from 0.13 to 0.52 uM and 0.32 to 0.64 uM, respectively, in solution to avoid nutrient deficiency problems.

Throughout the Phase V biological test, door seals were kept continuously inflated except to enter the chamber for maintenance or measurements near the plant canopy. This allowed accurate monitoring of CO_2 and water exchange throughout the entire study, and a detailed report of the gas exchange results is currently in draft. Briefly, the results showed peak CO_2 uptake

(photosynthesis) by the stand occurred around 20 to 25 days after planting. This was followed by a gradual decline as the stand matured. Dark period respiration also peaked near 20 to 25 days. As in the previous test, stand photosynthesis increased in a linear fashion with PPF (750 umol m^{-2} s^{-1} the highest level tested), with a compensation point near 220 umol m^{-2} s^{-1} (Corey, 1989). Stand photosynthesis appeared to be uniform across the light period, showing no diurnal trends. Cross-checks of photosynthetic calculations using closed system CO_2 drawdowns against semi-closed, CO_2 mass flow meausurements (see Coombs et al., 1985) showed close agreement (Corey, 1989). Water transpired by the stand peaked near 25 days and remained nearly constant for the remainder of growth.

In addition to CO_2 and water, atmospheric samples were taken daily and analyzed using gas chromatography (photoionization detector--PID) for light hydrocarbons. Results showed that ethylene gas increased from about 10 ppb at the beginning of the study to about 120 ppb circa day 30 (B. Vieux, unpublished). This was followed by a gradual decline back to a less than 10 ppb at 70 days.

During the time of flag leaf expansion and head emergence (days 30 through 40), flag leaves began to show a pronounced epinastic rolling along the longitudinal axis, somewhat resembling a "soda straw". Despite this rolling, the leaves were transpiring rapidly (as measured with a steady-state porometer) and stand photosynthesis seemed unaffected. Several leaves were excised and removed from the chamber for extraction of intercellular gas and analysis using gas chromatography (Beyer and Mor-

gan, 1970). Although tests were variable, tissue ethylene levels were as high as 400 ppb. On day 38, four trays were removed from the chamber and placed in a growth chamber under similar conditions (except fluorescent radiation at 300 umol m^{-2} s^{-1} instead of HPS radiation at 600 umol m^{-2} s^{-1}) but a low ethylene (<10 ppb) environment for 5 days. Repeating tissue gas extractions after 5 days in this environment showed that tissue ethylene levels had dropped to less than 100 ppb, but flag leaves remained rolled.

As with the Phase IV test, growth was again disappointing. After 85 days, a total of 44.24 kg of biomass was produced, or 32.5 g m^{-2} day^{-1}--only 56% of optimal yields (Bugbee and Salisbury, 1988). As before, seed set was low, with an average harvest index of 30%. Interestingly, total biomass from the fourth level averaged 38.2 g m^{-2} day^{-1}, about 66% of optimal yield and 17% better than the chamber average (Table 2). Throughout growth, plants on the fourth level appeared generally healthier and more robust than plants in the rest of the chamber. Leaves of plants on the other levels, particularly levels 1 and 2, showed numerous chlorotic flecks and more leaf tip burn. Other than the cooler temperatures early in development, no obvious environmental differences existed between the fourth level and the rest of the chamber. In addition, the leaf rolling symptoms were as prevalent on plants of fourth level as in the rest of the chamber. Thus the cool temperatures early in development may have had some favorable influence on development. Follow-up studies comparing cultural techniques are currently underway to study this problem further.

SUMMARY

The Biomass Production Chamber at Kennedy Space Center was constructed to conduct large-scale plant growth studies for NASA's CELSS program. Over the past four years (1985-1989), physical systems and computer control software have been continually upgraded and the degree of atmospheric leakage from the chamber has decreased from about 40% to near a 5% (total volume per day). Only within the past year (1989) have nearly all of the originally desired control capabilities been implemented. During the chamber development, five separate biological tests were conducted using wheat, one of the primary candidate crops. Early tests conducted with a limited degree of atmospheric closure showed that total crop growth from the best trays was within 80% of reported optimal for similar level of photosynthetically active radiation. Yields from subsequent tests under more tightly closed conditions have not been as good--up to only 65% of optimal yields for the best trays. Yields appear to have decreased with increasing atmospheric closure, yet potential problems exist in cultural techniques and further studies are warranted. With the ability to tightly seal the chamber, quantitative data have been gathered on CO_2 and water exchange rates. Results showed that wheat stand photosynthesis reached a peak near 25 days after planting, soon after full vegetative ground cover was established, and then gradually decreased with maturity. Stand photosynthesis increased linearly with increasing PPF (750 umol m^{-2} s^{-1} maximum tested) with a light compensation point near 200 umol m^{-2} s^{-1}. Stand photosynthetic rates did not increase much as CO_2 levels were raised beyond 1000 ppm, but

dropped sharply when CO_2 levels fell below approximately 700 ppm. Dark period respiration of the stands could be increased markedly if temperatures were increased from 16° to 24°C. Water transpiration from the wheat stands appeared to reach a maximum soon after full vegetative ground cover and remained nearly constant until near senescence. In the final phase of testing when atmospheric closure was the highest, ethylene gas levels in the chamber atmosphere rose from about 10 ppb to nearly 120 ppb during middle growth after which concentrations decreased to near 10 ppb. Evidence suggests that the ethylene originated from the wheat plants themselves and may have caused an epinastic rolling of the leaves, but no apparent detrimental effects on whole plant function.

The Biomass Production Chamber has been steadily improved both in the scope and precision of control system capabilities. The information on productivity, water cycling, nutrient balance, and microbiological enumeration and identification are unique physiological and ecological data sets. The reduction in yield with increasing closure raises interesting and critical areas for further studies. Program support has not kept pace with the scheduled development of the BPC and specific instrumentation and operation requirements of the biomass production tests have not been met due to the lack of resources. It is our hope that future resources will allow total utilization of this facility, which should continue to serve as an invaluable tool for the CELSS program.

LITERATURE CITED

Beyer, R.M. and P.W. Morgan. 1970. A method for determining the concentration of ethylene in the gas of vegetative plant tissue. Plant Physiol. 46:352-354.

Bingham, G.E. and P.I. Coyne. 1979. Spectral distribution of dimmed HID lamps in a plant growth facility. Agron. J. 71:513-515.

Bugbee, B.G. and F.B. Salisbury. 1988. Exploring the limits of crop productivity. I. Photosynthesis efficiency of wheat in high irradiance environments. Plant Physiol. 88:869-878.

Bugbee, B.G. and F.B. Salisbury. 1989. Controlled environment crop production: Hydroponic vs. lunar regolith. In: D.W. Ming and D.L. Henninger (eds.), Lunar Base Agriculture: Soils for plant growth. Amer. Soc. Agron., Madison, WI, USA.

Chung, G.C., R.N. Rowe, and R.J. Field. 1989. Solution depth affects root morphology and growth of cucumber plants grown in circulating nutrient solution. J. Am. Soc. Hort. Sci. 114:890-893.

Coombs, J., D.O. Hall, S.P. Long, and J.M.O. Scurlock. 1985. Techniques in bioproductivity and photosynthesis. Pergamon Press, London.

Corey, K.A. 1989. Dynamics of carbon dioxide exchange of a wheat community grown in a semi-closed environment. Report to Kennedy Space Center Summer Falculty Fellowship Office.

Graves, C.J. 1983. The nutrient film technique. Hort. Rev. 5:1-43.

Krizek, D.T. 1978. Air movement. In: R.W. Langhans (ed.), A Growth Chamber Manual. Cornell Univ. Press, Ithaca, NY, USA.

Mackowiak, C.L., L.P. Owens-Hall, C.R. Hinkle, and R.P. Prince. 1990. Continuous hydroponic wheat production using a recirculating system. NASA Tech. Memorandum (In Press).

Marschner, H. 1986. Mineral nutrition of higher plants. Academic Press, London.

Prince, R.P., W.M. Knott, J.C. Sager, and S.E. Hilding. 1987. Design and performance of the KSC biomass production chamber. Soc. Automot. Eng. (SAE) Paper 871437, Seattle, WA, USA.

Prince, R.P. and W.M. Knott. 1989. CELSS breadboard project at the Kennedy Space Center. In: D.W. Ming and D.L. Henninger (eds.), Lunar Base Agriculture: Soils for Plant Growth. Amer. Soc. Agron., Madison, WI, USA.

Sager, J.C., C.R. Hargrove, R.P. Prince, and W.M. Knott. 1988. CELSS atmospheric control system. Amer. Soc. Ag. Eng. (ASAE) Paper 88-4018, St. Joseph, MI, USA.

Sager, J.C., J.L. Edwards, and W.H. Klein. 1982. Light energy utilization efficiency for photosynthesis. Trans. ASAE 25:1737-1746.

Salisbury, F.B. and B. Bugbee. 1988. Plant productivity in controlled environments. HortScience 23: 293-299.

Sokal, R.R. and F.J. Rohlf. 1981. Biometry. W.H. Freeman and Comp., New York.

Table 1. Time course of physical systems development of NASA's Biomass Production Chamber (BPC). Developments for 1985 through 1989 have been divided into five phases roughly coinciding with biological (crop) tests. Actual values listed depict set points used for the biological tests.

PARAMETER	PHASE				
	I	II	III	IV	V
	(Jan 1985-Aug 1987)	(Aug 1987-Aug 1988)	(Aug 1988-Jan 1989)	(Jan 1989-May1989)	(May 1989-Nov 1989)
Atmospheric Closure	Open	Semi-sealed	Semi-sealed	Sealed but door gaskets not always activated	Sealed
Leakage Rate (% vol/day)	>60%	20-40%	10-20%	5-10%	<5%
System modifications		Installed and closed nutrient solution systems, added pneumatic gaskets to doors	Sealed air duct connections,sealed air filter housings	Water seal of fan shafts	Sealed between fan shaft pillow blocks and fan housings
Atmospheric Monitoring(M) & Control(C)					
Temperature (°C)	23 (C)	23 (C)	20/16 (C)	20/16 (C)	20/16 (C)
Relative Humidity (%)	65% (C) (dehumidification only)	65% (C) (dehumidification only)	65% (C) (dehumidification only)	65% (C)	75% (C)
Carbon Dioxide (ppm)	atmospheric	1000 (C)	1000 (C)	1000 (C)	1000 (C)
Oxygen (%)	20.8 (M)	20.8 (M)	20.8 (M)	20.8 (M)	20.8 (M)
Pressure (mm H_2O)	atmospheric	atmospheric	atmospheric (± 12)	atmospherhic (M) (± 10-100)	atmospheric (M) (± 10-100)
Ozone (ppb)	40-60 (M)	40 (M)	40 (M)	—	—
Ethylene (ppb)	—	—	—	10-20 (M)	10-120 (M)

Footnotes: (M)= monitored only; (C)= monitored and controlled

Table 1. (Cont'd)

PARAMETER	PHASE				
	I	II	III	IV	V
Nutrient Delivery Systems					
Reservoir Nutrient Solution	Temporary tank Mod. 1x Hoagland FeHEDTA & EDDHA Silicon added	Perm. tanks (1&2) Mod. 1/2xHoagland FeEDTA	Perm. tanks (1-4) Mod.1/2xHoagland FeEDTA	Perm. tanks (1-4) Mod.1/2xHoagland FeEDTA	Perm. tanks (1-4) Mod. 1/2xHoagland FeEDTA Silicon added initially Copper increased (4X) Zinc increased (2X)
Electrical Conductivity (dS m^{-1})	2.4 (Manual Control)	1.2 (Manual Control)	1.2 (Manual Control)	1.2 (Computer Control)	1.2 (Computer Control)
pH	6.2 (Manual Control)	6.0 (Auto Controller)	6.0 (Auto Controller)	6.0 (Computer Control)	6.0 (Computer Control)
Temperature (^{o}C)	23 (Controlled)	—	—	—	—
Lighting System					
Lamp Type	HPS (400-W)	HPS	HPS	HPS	HPS
Photoperiod (hrs L/D)	24 (no control)	24 (no control)	20/4	20/4	20/4
PPF (umol $m^{-2}s^{-1}$) Range/Average	500-900/---	500-900/666	500-600/509 (dimming system used)	500-600/535 (dimming system used)	600-750(691) (end reflectors added)
Ave Daily PPF (mol $m^{-2}day^{-1}$)	—	51.5	36.6	38.5	49.7
Computer Monitoring of PPF	—	2 sensors	2 sensors	4 sensors	4 sensors

Table 1. (Cont'd)

PARAMETER	PHASE				
	I	II	III	IV	V
Additional Measurements (manual)					
PPF (quantum sensor)	Weekly	Weekly	Weekly	Weekly	Weekly
Air Temp. (thermistor)	Weekly	Weekly	Weekly	Weekly	Weekly
Canopy Temp. (infrared therm.)	—	Weekly	Weekly	Weekly	Weekly
Air Velocity (hot-wire anemometer)	—	Weekly	Weekly	Weekly	Weekly
Spectral Distribution (spectroradiometer)	—	Numerous sets during dimming tests	—	—	—
Nutrient Solution Analysis (elemental)	2x/week	Weekly	Weekly	Weekly	Weekly
Nutrient Solution Alalysis (microbial)	—	Weekly	—	2x/week	2x/week
Condensate Analysis	—	Weekly	Weekly	Weekly	Weekly
Condensate Analysis (microbial)	—	Weekly	—	2x/week	2x/week
Plant Tissue Analysis (elemental)	First harvest	20-days & first harvest	—	Weekly	Weekly
Atmospheric Analysis (microbial)	—	Weekly	—	Weekly	Weekly

Table 2. Results of biological tests conducted in NASA's Biomass Production Chamber.

PARAMETER	PHASE I (Dec 1986-Apr 1987)	II (May 1988-Aug 1988)	III (Nov 1988-Jan 1989)	IV (Jan 1989-May 1989)	V (May 1989-Aug 1989)
System Set-Up					
Shelves (Levels) Used	2(upper chamber)	2(upper chamber)	4(total chamber)	4(total chamber)	4(total chamber)
Trays Used	32(intermittent)	32(continuous)	44(continuous)	64(continuous)	64(continuous)
Approximate Growing Area (m^2)	—	8	11	16	16
Experiment Measurements					
Total Water Added to Nutrient Solution (L)	—	3914	4231	6430	7762
Ave. Rate of Water Added (L m^{-2} day^{-1})	—	6.6	5.9	4.7	5.7
Total Water Condensed (L)	—	3615	3637	6904	7376
Ave Rate of Condensation (L m^{-2} day^{-1})	—	6.1	5.1	5.0	5.4
Total Acid for pH Control (L Conc. HNO_3)	—	1.87	1.70	2.74	3.96
Ave. Rate of Acid Addition (ml m^{-2} day^{-1})	—	3.1	2.40	2.0	2.9
Total Nutrient Stock Solution Added (L)	—	178	315	400	406
Ave. Rate of Stock Solution Addition (L m^{-2} day^{-1})	—	0.30	0.44	0.29	0.30

Table 2. (Cont'd)

PARAMETER	PHASE				
	I	II	III	IV	V
Ave. Light Period CO_2 Uptake					
(L day^{-1})	—	—	—	517 (20°C)	639 (20°C)
(umol m^{-2} s^{-1})	—	—	—	18.7 (20°C)	23.1 (20°C)
Ave Dark Period CO_2					
Production (L day^{-1})	—	—	—	49 (16°C)	57 (16°C)
(umol m^{-2} s^{-1})	—	—	—	9.0 (16°C)	10.5 (16°C)
Final Harvest Results					
Plant Age (days)	—	74	65 (Early Harvest)	86	85
Total Biomass (Ave)					
(g DW/tray)	—	721	594	590	691
(g m^{-2})	—	2884	2376	2360	2764
(g m^{-2} day^{-1})	—	39.0	36.6	27.4	32.5
Total Biomass (Best Four Trays)					
(g DW/tray)	—	908	786	684	857
(g m^{-2})	—	3632	3144	2736	3428
(g m^{-2} day^{-1})	—	50.4 (72 days)	48.4	31.8	40.3
Seed Yield (Ave)					
(g DW/tray)	—	289	—	172	205
(g m^{-2})	—	1156	—	688	820
(g m^{-2} day^{-1})	—	15.6	—	8.0	9.6
Seed Yield (Best Four Trays)					
(g DW/tray)	—	391	—	207	302
(g m^{-2})	—	1564	—	828	1208
(g m^{-2} day^{-1})	—	21.7 (72 days)		9.6	14.2
Harvest Index					
Total (%)	—	40	—	29	29
Best Four Trays (%)	—	43	—	30	35

NASA

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM 103494		

4. Title and Subtitle
System Development and Early Biological Tests with NASA's Biomass Production Chamber

5. Report Date
April 1990

6. Performing Organization Code
BIO-3

7. Author(s)
Wheeler, R.M., C.L. Mackowiak, T.W. Dreschel, J.C. Sager, R.P. Prince, W.M. Knott, C.R. Hinkle, and R.F. Strayer

8. Performing Organization Report No.

10. Work Unit No.

9. Performing Organization Name and Address
The Bionetics Corp. (RMW, CLM, TWD, CRH, RFS)
NASA Biomedical Operations and Research (JCS, RPP, WMK)
Kennedy Space Center, FL 32899

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

13. Type of Report and Period Covered

14. Sponsoring Agency Code
MD/RES

15. Supplementary Notes

16. Abstract The Biomass Production Chamber at Kennedy Space Center was constructed to conduct large-scale plant growth studies for NASA's CELSS program. Over the past four years (1985-1989), physical systems and computer control software have been continually upgraded and the degree of atmospheric leakage from the chamber has decreased from about 40% to 5% of the total volume per day. Early tests conducted with a limited degree of closure showed that total crop (wheat) growth from the best trays was within 80% of reported optimal yields for similar light levels. Yields from subsequent tests under more tightly closed conditions have not been as good--up to only 65% of optimal yields. Yields appear to have decreased with increasing closure, yet potential problems exist in cultural techniques and further studies are warranted. With the ability to tightly seal the chamber, quantitative data have been gathered on CO_2 and water exchange rates. Results showed that stand photosynthesis and transpiration reached a peak near 25 days after planting, soon after full vegetative ground cover was established. In the final phase of testing when atmospheric closure was the highest, ethylene gas levels in the chamber rose from about 10 ppb to nearly 120 ppb. Evidence suggests that the ethylene originated from the wheat plants themselves and may have caused an epinastic rolling of the leaves, but no apparent detrimental effects on whole plant function.

17. Key Words (Suggested by Author(s))
CELSS, Controlled Ecological Life Support Systems, Bioregenerative Life Support Systems, Photosynthesis, Transpiration, Ethylene, Carbon Dioxide, CO_2, Light, Irradiance, PPF

18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	29	