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From Project Mercury to the Breadboard Project

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NASA's Project Mercury began as a response to the cold war with the Soviet Union and had a number of goals: to place a manned spacecraft in orbital flight around the earth; to investigate man's performance capabilities and his ability to function in the environment of space and to recover the man and the spacecraft safely. An aspect of preflight testing included the use of an altitude chamber to test each capsule and allow the astronauts to engage in simulated missions within a vacuum environment. In 1985, the chamber was modified for an unusual mission. During 1985 into 1987, the chamber was converted to an environmentally-controlled, hydroponic plant growth chamber termed the "Biomass Production Chamber". The chamber hosted crop studies of wheat, soybean, lettuce, potato, and tomato and demonstrated intensive, closed environment farming until decommissioned in late 2001. Significant findings included: the nutrient solution could be reconstituted without replacement for at least four crop cycles; cooling the nutrient solution was important for potato crops and; redundant sensor systems were important to ensure consistent control and data collection.

Nomenclature

CELSS	=	Controlled Ecological Life Support Systems
BPC	=	Biomass Production Chamber
NASA	=	National Aeronautics and Space Administration
USSR	=	Union of Soviet Socialist Republic
US	=	United States
PAR	=	Photosynthetically Active Radiation

I. Introduction

Rocketry likely had its origins with the discovery of saltpeter (potassium nitrate) due to its abundance in China and India. The utilization of a mixture of saltpeter with charcoal and sulfur to propel a projectile was first documented as by the Mongols in the battle of Pieping in 1232 A.D. (T-hung-lian-kang-mu, cited in Ref. 1). In the mid-15th century, rockets were consistently used as weapons as well as for signaling, and these applications continue to this day. The specific use of rockets to carry living creatures began in the early 19th century but it wasn't until the late 19th to early 20th century before it was proposed that a rocket could operate in a vacuum and be used for spaceflight. During this latter period, rocket designs using alternate fuels were considered and in fact, in 1907, Robert Goddard proposed the use of radioactive materials for interplanetary travel.[1]

Following World War II, the United States (US) and the Soviet Union (USSR) became engaged in what was called a "cold war" during which both countries worked to get an upper hand on the technology that would make them a superior power. One area of competitive development was in astronautics. The successful launch of Sputnik I by

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the USSR provided the impetus for the US to develop a manned spaceflight program. The first manned project in this program was Project Mercury. Seven military pilots were recruited to become the first US astronauts: Alan B. Shepherd, Jr.; Virgil I. Grissom; John H. Glenn, Jr.; M. Scott Carpenter; Walter M. Schirra, Jr.; L. Gordon Cooper, Jr.; and Donald K. Slayton. For initial testing of the Project Mercury spacecraft and the Redstone rocket, a chimpanzee named Ham was launched into a suborbital flight by the US in January 1961. In April that year, the USSR launched Major Yuri Gagarin into an orbital flight. This provided impetus to push the Mercury Program rapidly forward.[2]

NASA's Project Mercury's goals were: to place a manned spacecraft in orbital flight around the earth; to investigate man's performance capabilities and his ability to function in the space environment, and to recover the man and the spacecraft safely.[3] One aspect of preflight testing included the use of an altitude chamber to test each capsule and allow the astronauts to engage in simulated missions within a vacuum environment. This chamber construction was completed in Hangar S at Cape Canaveral Air Force Station, Florida in 1960, after which, it was used to verify the integrity of the Mercury spacecraft. Following the completion of Project Mercury, the chamber was modified to accommodate Project Gemini spacecraft.[4]

Flash forward to 1985. The Biomedical Operations and Research Office at Kennedy Space Center proposed to use the chamber for an unusual mission. During 1985 into 1987, the chamber was moved to Hangar L at Cape Canaveral Air Force Station and converted to an environmentally-controlled, hydroponic plant growth chamber termed the "Biomass Production Chamber". Windows were removed and plates welded on the openings and a floor was installed, separating the chamber into two sections, an upper and a lower. The upper section was accessible through the airlock and a sealable door was installed in the lower section.[5]

Sealed air handling systems were added to both upper and lower sections, which included the installation of ductwork to maintain temperature by cooling the lighting fixtures and the plant growth area. Four shelves consisting of eight racks, each supported height-adjustable sections and light banks with six 400-Watt High Pressure Sodium lamps, were arranged in a circular pattern to fit the upright, cylindrical geometry of the chamber. Each shelf provided 5 m^2 of growing area, and a total of four shelves were stacked vertically in the chamber, providing a total of 20 m^2 of growing area. Each shelf supported a total of 16 hydroponic trays for growing crops. The chamber hosted a plethora of crop production studies (22) from 1987 through late 2001, after which it was decommissioned.[6,7]

II. NASA's Project Mercury

NASA's Project Mercury had a number of goals: to place a manned spacecraft in orbital flight around the earth; to investigate man's performance capabilities and his ability to function in the environment of space and to recover the man and the spacecraft safely. Important aspects of the Mercury Program were: the spacecraft must be fitted with a reliable launch-escape system to separate the spacecraft and its crew from the launch vehicle in case of impending failure; the pilot must be given the capability of manually controlling spacecraft attitude; the spacecraft must carry a retrorocket system capable of reliably providing the necessary impulse to bring the spacecraft out of orbit; a zero-lift body utilizing drag braking would be used for reentry; the design must satisfy the requirements for a water landing.[2,3]

One aspect of preflight testing included the use of an altitude chamber to test each capsule and allow the astronauts to engage in simulated missions within a vacuum environment. Tenney Engineering Corporation was chosen by the Space Task Group to construct the Mercury altitude test chamber in Hangar S at Cape Canaveral Air Force Station, Florida. When completed, chamber pressure would simulate 225,000 feet in altitude.[8]

The chamber, a vertical cylinder with domed ends, was 12 feet (3.7 m) in diameter and 14 feet (4.3 m) high. The chamber was designed to allow a partial spacecraft functional check in a near-vacuum environment. Construction of the altitude facility chamber to simulate the space environment was completed in Hangar S at Cape Canaveral (Figure 1). The purpose of this facility was for spacecraft checkout and astronaut training. Acceptance tests for this installation were completed on July 11, 1960. The chamber was used to simulate the vacuum of the space environment that the Mercury capsules would experience during each mission and used for simulations of all of the Mercury missions (Figure 2).

Following the completion of the Mercury program in May of 1963, the chamber was to be moved to the Operations and Checkout building at Kennedy Space Center for Gemini spacecraft testing. The chamber was elongated by 9 feet (2.7 m) with a bottom section added and additional enhancements implemented (Figure 3).[4]

III. The NASA Breadboard Project

Flash forward to 1985. The Mercury/Gemini Altitude Chamber was now destined for use in another unusual mission. The Biomedical Operations and Research Office at Kennedy Space Center proposed to build and operate The Breadboard Project facility for research in support of the NASA Controlled Ecological Life Support Systems (CELSS) Program. The CELSS Program was a NASA effort to develop a system that would provide the basic life support

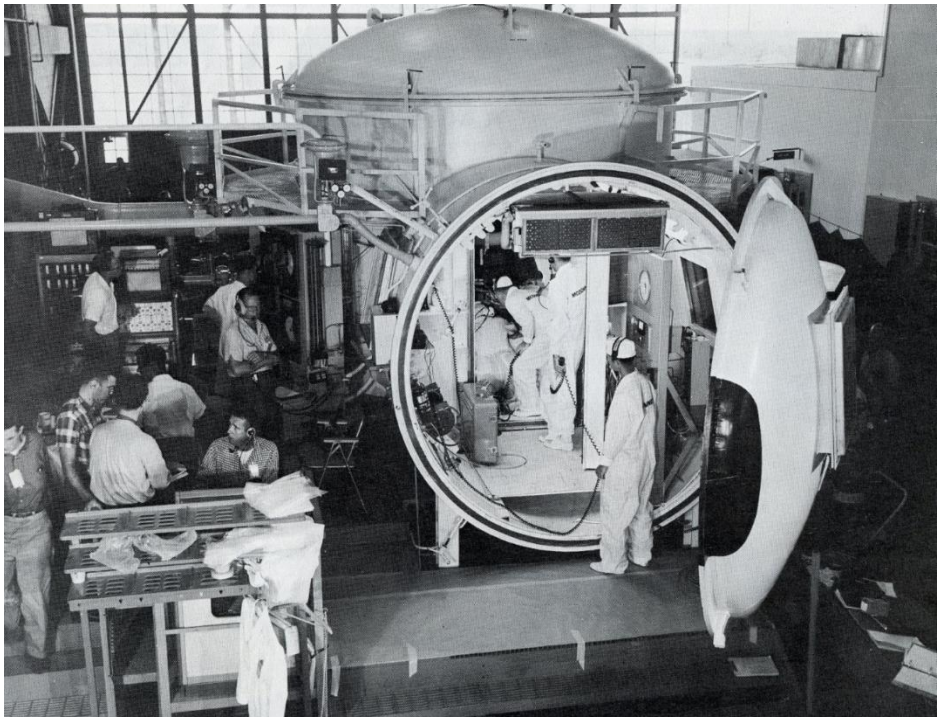

Figure 1. The Mercury Program Altitude Chamber in Hangar S, Cape Canaveral Air Force Station, Florida. ***Credits: NASA***

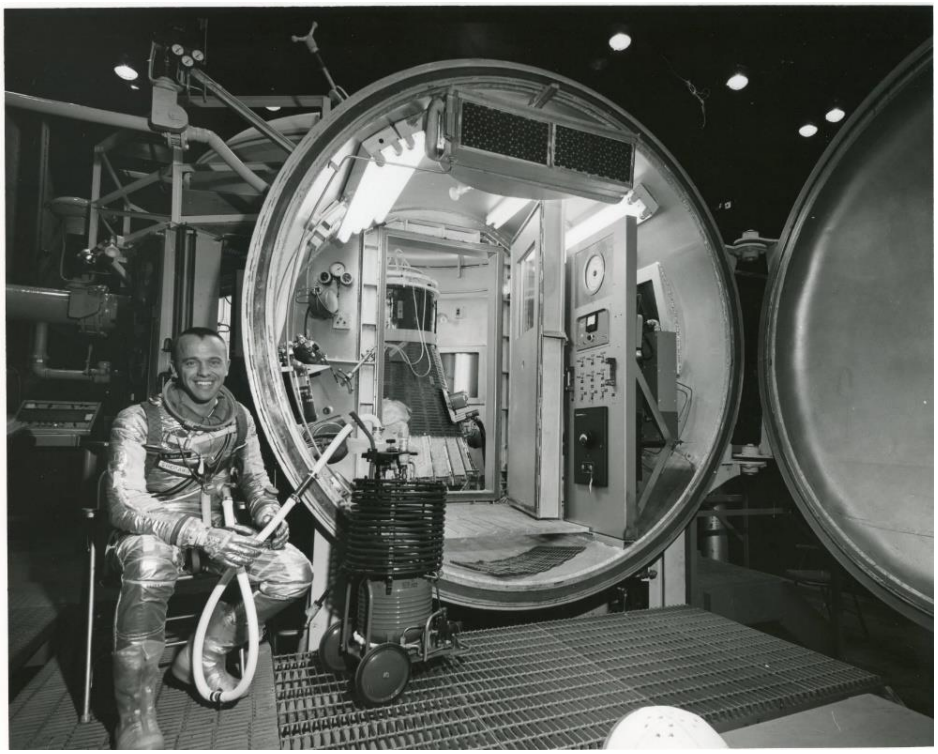

Figure 2. Astronaut Alan B. Shepherd, Jr. with the Mercury Altitude Chamber containing the Freedom 7 spacecraft. ***Credits: NASA***

Figure 3. The Mercury/Gemini Altitude Chamber, moved to Hangar L, Cape Canaveral Air Force Station, Florida. *Credits: NASA*

requirements such as food, potable water, and breathable atmosphere (carbon dioxide removal and oxygen production) for crews on long term space missions or for planetary colonies. CELSS work was carried out through NASA funded research at universities, and work at NASA field centers, including Ames Research Center, Kennedy Space Center, and Johnson Space Center.[9] CELSS research included areas such as food production systems to grow crop plants and algae under controlled conditions; food processing systems to derive the maximum edible content from all plant parts; waste management systems to recover and recycle all solid, liquid, and gaseous components necessary to support life, and systems integration and control.[10-12]

The Breadboard facility at Kennedy Space Center implemented CELSS research on a functional scale, and allowed scientists and engineers to operate such a system and collect critical data for constructing an off-world CELSS. The CELSS Breadboard Facility was designed to provide the hardware and systems and to develop the techniques for the production of food and oxygen, removal and reduction of carbon dioxide, the preparation of food and the processing of waste in a controlled recycling system.[12]

The Breadboard Project[12] goals were:

1. To fabricate, test, and operate ground based CELSS systems modules to accomplish proof-of-concept testing and the evaluation of operations in a "breadboard" facility of a practical size.
2. To characterize system operations, mass and energy budgets, and to determine from tests of the Breadboard facility what performance could be obtained from a full-sized operational CELSS.

The Breadboard Project Plan described the physical dimensions and limitations of the Mercury/Gemini altitude chamber to be converted to the Biomass Production Chamber (BPC) given the original purpose and subsequent modifications (Table 1). In addition, the plan described the control specifications and limits that the chamber had to be operated within to provide an adequate controlled environment for the crop production demonstration appropriate for space colonization (Table 2).

Table 1. Physical Specifications for the BPC[12]

PARAMETER	SIZE
Diameter	3.7 m
Height	
Overall	7.0 m
Internal Compartment (each)	2.7 m
Area	
Section	10.1 m^2
Plant Growth	20 m^2
Volume	
Chamber	74 m^3
Plant Growth	54 m^3
Chamber plus Air Ducting	113 m^3

Table 2. Control Specifications for the BPC[12]

	LIMIT			
PARAMETER	LOW	HIGH	CONTROL ERROR	MONITORING SENSITIVITY
Photosynthetically-active radiation at plant level (µmol s^{-1} m^{-2})	200	1000	N/A	N/A
Photoperiod (min.)	No light	continuous	15	N/A
Temperature (^oC)				
light	18	30	1	0.2
dark	18	30	1	0.2
Humidity (%RH)	60	70	10	5
Carbon dioxide (ppm)	300	2500	10%	10
Oxygen (%)	19.5	20.9	10%	1
Nitrogen (%)		78.1	Monitor only	1
Air movement across leaf canopy (m s^{-1})	1	3	0.2	
Leak rate	Not detectable by bubble test at 2 in. of H_2O			
Pressure (in. of H_20)	1	2	0.5	0.1

IV. Biomass Production Chamber Construction

During 1985 into 1987, the Mercury/Gemini altitude chamber was converted to an environmentally-controlled hydroponic plant growth chamber termed the "Biomass Production Chamber" or BPC. Windows were removed with plates welded on the openings. A floor was installed, separating the chamber into two sections, an upper and a lower. Sealed air handling systems were added to both the upper and lower sections, which included the installation of

ductwork to circulate air and maintain temperature by cooling the lighting fixtures and the plant growth areas. The upper section was accessible through the airlock and a sealable door was installed in the lower section (Figure 4).

The BPC's size was deemed adequate to provide the food needs for approximately one person plus water, and atmospheric regeneration for more than one person, due to additional production of inedible biomass by the plants.[13,14] The conversion of the BPC was to add an air handling system (ductwork, blowers, temperature control) to the upright cylindrical chamber (7.5 m high, 3.7 m in diameter). It had two operational levels with direct access to each (Figure 4). There was also a hatch between the lower and upper levels. Four annular crop growing shelves with associated light fixtures, were stacked vertically (two per story). Each shelf provided about 5 square meters of crop growing area resulting in a total area of 20 square meters.

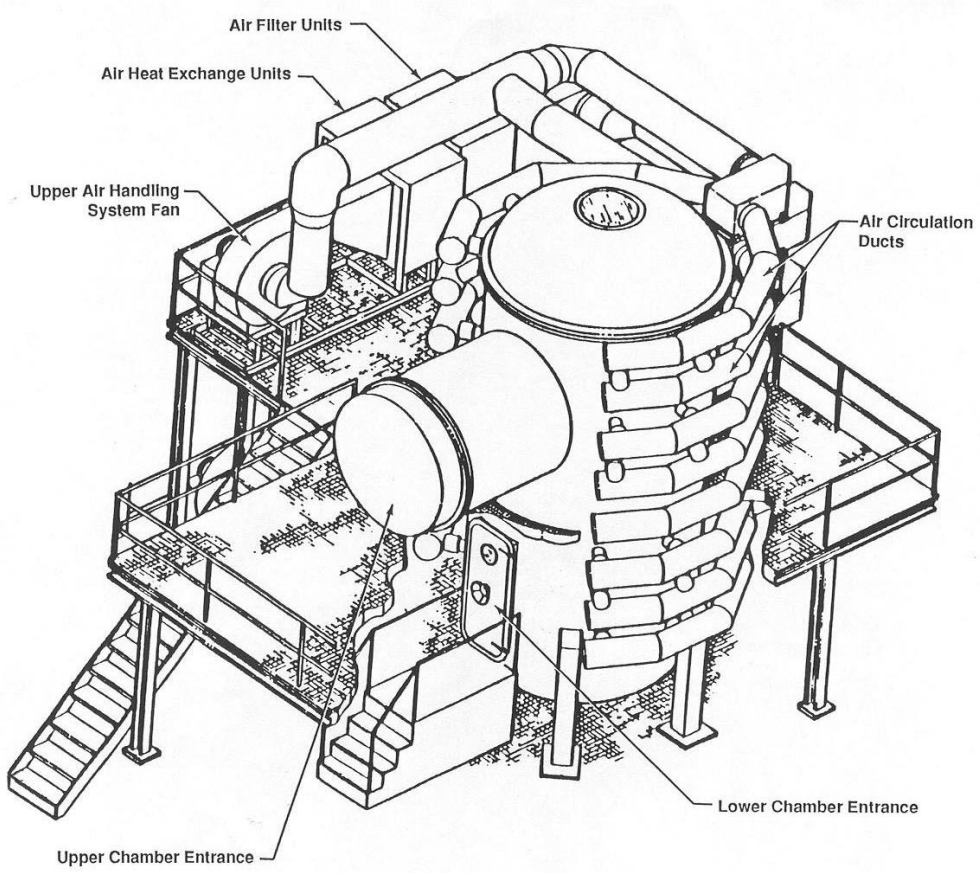

Figure 4. The design of the Biomass Production Chamber. ***Credits: NASA***

Concurrent with the modifications of the chamber, a control and data collection capability (Control Room) was constructed to enable the monitoring and control of all aspects of operating the BPC. The control system utilized sensors, control valves, switches connected to a programmable logic controller (PLC). The PLC was programmed to maintain the environmental, liquid and gas parameters to within specified limits. It also managed alarms and was programmed to shut down certain subsystems if out-of-range limits were reached. A separate set of sensors was installed for the specific purpose of monitoring all the parameters associated with chamber control and many parameters having to do with the particular experiment. The dataset consisted of five minute averages taken over one minute intervals. The chamber was designed to be capable of controlling the light, temperature, humidity, carbon dioxide and oxygen levels, atmospheric pressure and air flow rates, with the upper and lower sections being independent of one another (Figures 4, 5).[7] The air handling system was designed to allow for the condensate water from plant evapotranspiration to be recycled to the hydroponic system, closing the water loop. The entire internal volume of the BPC (including the air ducts) was 113 cubic meters. The air was circulated at about 400 m^3 min^{-1} by two 30 kW fans. Two copper heat-exchange coils were used for cooling and dehumidification (one in the upper and one in the lower air handling system). Chilled water from two 15-ton (53 kW) chilling units (these were later replaced

by a single 40-ton (140 kW) unit) provided the cooling. In addition, each cold coil was followed by a reheat coil that was supplied by hot water from heating elements (up to 150 kW capacity). One of two air handler units and condensate tanks are shown in Figure 6.

The atmospheric control system included a pressure tank to allow the maintenance of a set atmospheric pressure in the BPC (Figure 7, left). An off-the-shelf oxygen concentrator was used to maintain oxygen levels in the BPC at an appropriate level (~21%) when needed during sealed plant growth tests (Figure 7, right). Oxygen monitors for both levels were installed for confined space safety. Carbon dioxide was added from a dewer when necessary and monitored and controlled within the chamber, with oxygen monitored and controlled by opening the chamber or using the oxygen concentrator. Testing of the degree of seal with respect to time and total enclosed volume was conducted using the gas control and monitoring systems controlled within the BPC control room, with the lowest leakage rate being near 5% of the volume per day.[15] The BPC specifications were met with regards to seal and temperature and humidity.[16]

The four shelves consisted of eight racks, each supporting height-adjustable sections and light banks with six 400-W high pressure sodium lamps (to be later switched out with metal halide lamps) and arranged in a circular pattern to fit the upright, cylindrical geometry of the chamber (Figure 8). The lighting was controlled using dimming ballasts (external to the BPC) delivering About 2 kW of input electrical power per m^2 of growing area for plant growth, resulting in between about 300 to 800 µmol m^{-2} s^{-1} photosynthetically active radiation (PAR) at plant height, depending on the test. The lamps were separated from the plants by clear glass or acrylic barriers (Figure 8).

Each shelf provided 5 m^2 of growing area, and a total of four shelves were stacked vertically in the chamber, providing a total of 20 m^2 of growing area (Figure 8). Each shelf supported a total of 16 hydroponic trays for growing crops. Initially, the trays were constructed by welding pieces of polyvinyl chloride (PVC) sheeting together to form a tetrahedron shaped tray. Each tray was fitted with a germination cover which contained screening material that could be sprayed with water regularly to maintain sufficient humidity within the tray for seed germination. The PVC trays were replaced by deeper trays that were vacuum-formed from acrylonitrile butadiene styrene (ABS) plastic sheets in order to provide deeper trays for tuber crops (Figure 9).

Plumbing for the delivery and draining of the hydroponic solution for each hydroponic tray was installed. Each shelf in the racks supported two hydroponic trays for growing crops (Figure 9). Four hydroponics tanks and pumps were installed external to the chamber. Each tank supplied hydroponic solution to a separate annular set of shelves, two sets of shelves in the upper and two in the lower (Figure 9). Impeller pumps moved hydroponic solution from the bottom of each tank, through a set of coarse filters and past sensors for temperature, pH and conductivity prior to the solution being delivered to the plant chamber.

Once in the chamber, the solution was distributed to the back region (nearest the wall) of the 16 hydroponic trays and flowed as a thin film covering the bottom, to a drain in front empting into a return trough. The solution then drained back into the tank from where it was pumped (Figures 8, 9 and 10). The hydroponic solution pH was controlled to between 5.5 and 6.0 by the addition of dilute nitric acid, as the pH increased due to the removal of nutrients by the plants. The nutrient that had the greatest effect on pH as it was removed, was the nitrate in the hydroponic solution. Conductivity was used to indicate when additions of concentrated nutrients were required to be added to the hydroponic tanks to maintain nutrients concentrations similar to a one-half strength Hoagland's solution. The water levels were maintained initially by adding demineralized water each day. The main uptake of the water was due to plant transpiration, and ranged from less than 1 L m^{-2} day^{-1} to nearly 10 L m^{-2} day^{-1}, depending on the crop, the stage of development, and the environmental conditions.[17] For the condensate recycling system, the condensed humidity from transpiration was pumped through ion exchange columns to one of two holding tanks (depending upon BPC top or bottom) and used as make-up water for the hydroponic tanks, reducing the amount of external water needed to roughly that which was used for photosynthesis and incorporated into the plant tissue. Tray inserts and/or plant supports were designed and constructed as needed, depending upon the crop grown (Figures 8 and 9).

The headspaces of the hydroponic tanks were connected to the chamber to maintain atmospheric closure. The addition of air ducting and plumbing penetrations caused leakage and prevented large atmospheric pressure differentials from developing. Still, leakage could be maintained as low as 5 % of the chamber volume per day when the chamber was sealed.[18] Close tracking of CO_2 exchange rates and water recovery were possible during the sealed periods to allow the measurement of net photosynthesis, respiration and evapotranspiration. In addition, various volatile organic compounds were measured and production calculated using closed or semi-closed gas exchange calculations.[19,20] Additional engineering details and specifications can be found in Refs. 5, 6, 16, 20, 21, 22.

V. Biomass Production Chamber Crop Studies and Lessons Learned

Crop Studies: Wheat (6), soybean (4), lettuce (5), potato (5), and tomato (2) crops were grown hydroponically in the BPC from the late 1980s through 2001. Equivalent levels of CO_2 fixed (total = 1344 kg) and O_2 produced (total =

Figure 5. External view of the Biomass Production Chamber final configuration. ***Credits: NASA***

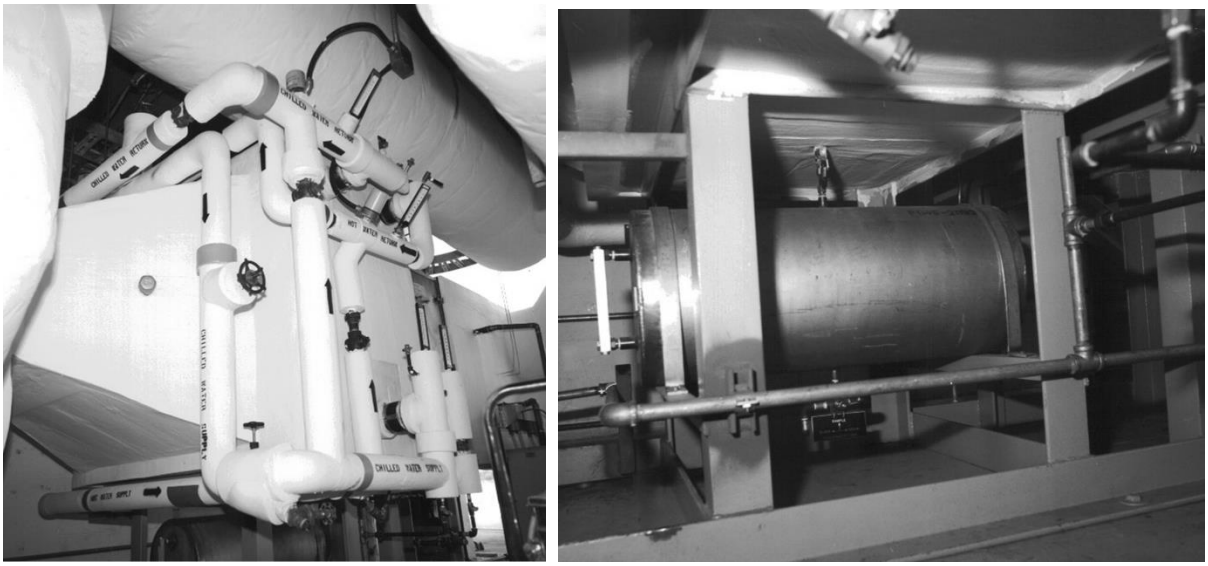

Figure 6. a) BPC air handler condenser (left) and b) condensate water collection tank (right). ***Credits: NASA***

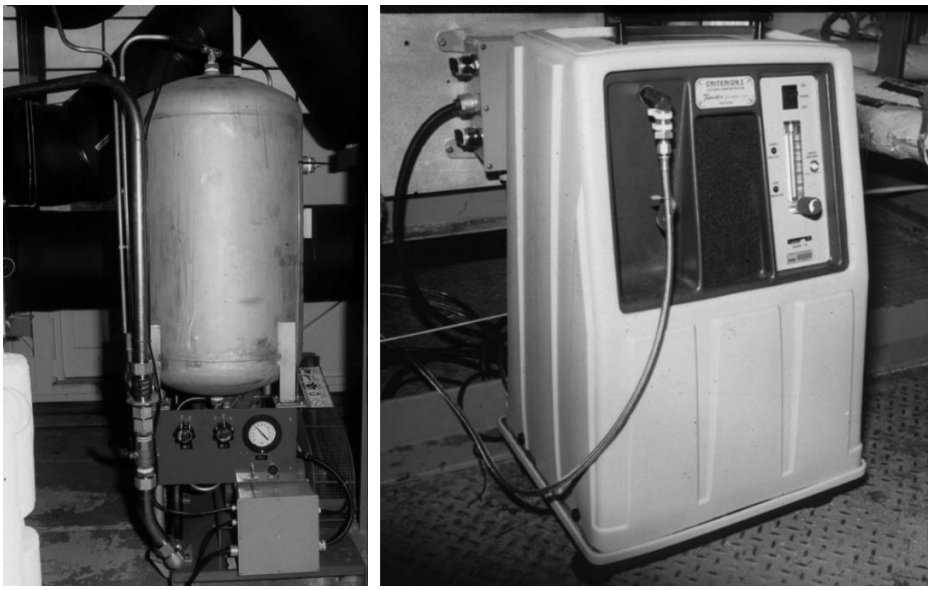

Figure 7. BPC atmospheric controls: a) The BPC atmospheric pressure control storage tank (left) and b) The oxygen concentrator (right). *Credits: NASA*

Figure 8. Internal views of the BPC showing the light banks and shelves, hydroponic trays and supporting plumbing. a) Upper left: wheat; b) Upper right; potato, with tray tops removed; c) Lower left: soybean; d) Lower right: Lettuce. *Credits: NASA*

Figure 9. The BPC hydroponic trays. a) Left: Original PVC tray with plant support insert and germination cover shown; b) Upper Right: Original PVC trays in the BPC with young wheat plants; c) Lower Right: BPC trays, vacuum-formed from ABS sheets containing potato tubers (potato tray tops removed). *Credits: NASA*

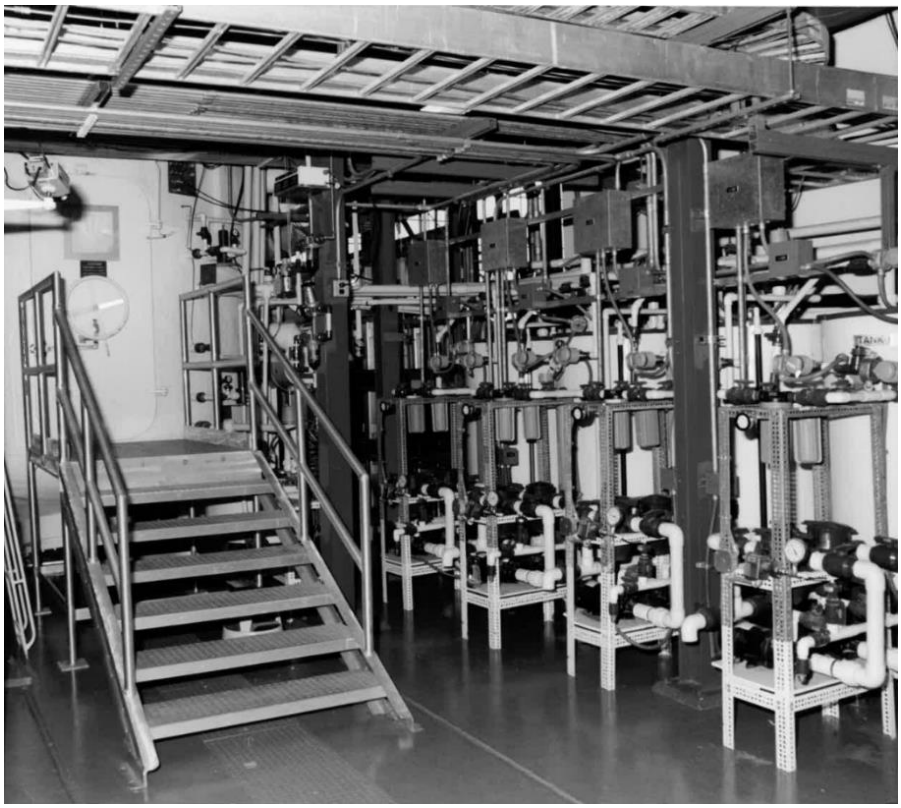

Figure 10. Hydroponics tanks, pumps and sensors (right) external to the BPC lower level. *Credits: NASA*

980 kg) were based on biomass carbon content and reported along with the total mass of water collected as condensate (total = 149,390 kg). The totals for each crop study can be found in Ref. 6. The highest biomass yields from BPC tests were obtained from wheat, which received the most PAR due to planting density (23.1 to 39.7 g m^{-2} d^{-1}). The greatest edible yields were obtained from potato, due to the fact that tubers can account for more than 80% of a potato plant's biomass. The radiation conversion efficiencies (light energy provided versus biomass produced) for the crops was from 0.4 to 0.9 g mol^{-1} for total biomass and from 0.2 to 0.6 g mol^{-1} for edible biomass.[23] This is similar to the 0.7 g mol^{-1} conversion value listed for corn under optimal field conditions.[24] In general, the crop biomass yield showed a near-linear response to photosynthetically active light energy[24] across the range of 15 to 60 mol m^{-2} d^{-1}.[23] Thus crop yield was directly related to light quantity in consideration for life support systems.[25]

Lessons learned: As with any engineering and research effort, particularly one in controlled environment agriculture, design specifications and horticultural techniques improved with experience.[7] Some more significant observations from the large-scale testing include:

1. The more penetrations made to a chamber, the more difficult it is to seal. This was learned early on in the development of the Mercury spacecraft. For the BPC, many hours were spent sealing internal penetration sites with silicone sealant. Interestingly, this likely resulted in the relatively high levels of siloxane volatiles measured in the chamber atmosphere,[26] and siloxanes are a concern for current trace contaminaint control systems on the International Space Station.
2. Any metal surfaces exposed to the hydroponic solution tend to dissolve metals such as nickel into the nutrient solution. Cooling coils used in the hydroponics tanks had to be jacketed with polyethylene tubing to avoid this contamination.
3. System alarms are critical to operating a hydroponic system of this scale. A sensor detecting solution spills was incorporated in the BPC bottom floor because of solution overflows due to the plugging drains, loss of tray integrity, etc.
4. Having redundant monitoring sensors along with control sensors for both atmospheric and nutrient solution management proved invaluable to avoid spurious control data.
5. Although the water coming from transpiration is essentially distilled water, during the condensation process it comes in contact with many surfaces (in the case of the BPC, the condensers were copper). Running the condensate through ion-exchange columns removed contaminants acquired during the condensate water processes and movement.
6. Wicks and high humidity within the trays were important for seed germination and seedling establishment, for wheat and lettuce in particular until the roots had reached the nutrient solution. Misting of seeds and seedlings on a daily basis and covering the trays promoted good seedling establishment. Providing two adjacent wicks for each seed was found to be the most effective.
7. Cooler nutrient solution temperatures were critical for potato tuber development. Consequently auxiliary cooling was used in the hydroponic tanks. Solution was controlled to around 18°C, increasing tuber yields.[27]
8. Shoot support was added to prevent lodging (stand collapse) for some crops. For most wheat, soybean, potato, and tomato studies, plant shoots were supported by wire mesh grids (Figures 8, 9).
9. Planting, harvesting and threshing of seed crops were labor intensive, dusty and required adequate ventilation or breathing masks for protection. Mechanized or even automated procedures are needed for seed crops.
10. KSC crop studies typically ran for one production cycle, except when the study called for continuous production.[28] One potato study ran for four successive generations (416 days) and was sustained without replacing the nutrient solution. Staggered plantings, conducted in two-tray blocks provided a more continuous yield and a more constant photosynthetic gas exchange.[6,29] The replanting created gaps in the plant canopy with staggered harvests likely adding side lighting, providing greater light energy.[29]
11. A growth regulating compound for potato was observed to accumulate in the nutrient solution over time.[30,31] This compound or factor resulted in reduced shoot growth and early tuber initiation.
12. When water pumps were inoperable due to losses of electrical power (e.g., thunderstorms, hurricanes) the trays were elevated at the drain end allowing the ponding of solution to keep the plants watered and minimize crop impacts.
13. Engineering (mechanical, electrical) and monitoring and control expertise (computer hardware and software as well as instrumentation) were important to the conversion of the chamber. Crop studies and hence food production aspects require expertise in plant lighting, horticulture, plant physiology, plant pathology and chemistry. Microbiology expertise continues to enable the evaluation of aspects related to plant and human health and new techniques in molecular biology will expand this capability. Advances in remote sensing

technologies will be essential to allow the crew time to attend to other tasks and not be required to spend significant time monitoring the crops.

VI. Moon, Mars and Beyond

The colonizing of other worlds will require learning how to sustainably provide all the needs for human life support as well as providing for the emotional and psychological needs of the colonists separated from Earth. The past and current manned spaceflight programs have provided evidence that humans can survive and even thrive in the space environment although microgravity and radiation require protection or countermeasures when experienced for long durations. The CELSS Breadboard Project and specifically the research and development associated with the operation of the Biomass Production Chamber provided data to inform the further design and construction of bioregenerative life support systems. The NASA vision of exploration continues with eyes fixed on returning to the lunar surface for greater durations and in doing so, learn how to explore and ultimately colonize Mars and other planetary bodies.

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References

[1]Gatland, K.W. and Kunesch, A.M. *Space Travel*, Pilosophical Library, Inc., New York, 1953, Chaps. 1-4.

[2]Collins, M. *Liftoff, The Story of America's Adventure in Space*, Gove Press, New York, 1988, Chaps. 2, 3.

[3]Grimwood, J.M. *Project Mercury: A Chronology. NASA SP-4001,* 1963.

[4]NASA. *News Release: KSC-132-64*, July 6, Kennedy Space Center FL, 1964.

[5]Prince, R.P., W.M. Knott, J.C. Sager and S.E. Hilding. Design and performance of the KSC biomass production chamber. *Soc. Automotive Eng. Tech. Paper 871437*, Seattle, WA, 1987.

[6]Wheeler, R.M., C.L. Mackowiak, G.W. Stutte, J.C. Sager, N.C. Yorio. L.M. Ruffe, R.E. Fortson, T.W. Dreschel, W.M. Knott, and K.A. Corey. NASA's Biomass Production Chamber: A testbed for bioregenerative life support studies. *Adv. Space Res.* 18 (4/5) 215-224, 1996.

[7]Wheeler, R.M., C.L. Mackowiak, G.W. Stutte, N.C. Yori, L.M. Ruffe, J.C. Sager, R.P. Prince, W.L. Berry, B.V. Peterson, G.D. Goins, C.R. Hinkle and W.M. Knott. Crop Production for Advanced Life Support Systems - Observations From the Kennedy Space Center Breadboard Project. NASA TM-2003-211184, John F. Kennedy Space Center, FL, 2003.

[8]North, W.J., Chief, Manned Satellite, to Director, Space Flight Development. Memo: *Request for Approval of Project Mercury Altitude Test Facility, Dec. 8, 1959*. (Ref. 3).

[9]Wheeler, R.M. Agriculture for space: People and places paving the way. Open Agriculture 2017 (2):14-32, 2017.

[10]MacElroy, R.D. (ed.). Controlled ecological life support systems: CELSS '89 Workshop NASA Technical Memorandum 102277, 1990.

[11]Knott, W.M. The Breadboard Project: A functioning CELSS plant growth system. *Adv. Space Res.* 12(5):45-52, 1992.

[12]Koller, A.M. *CBF, CELSS "Breadboard' Facility Project Plan.* Biomedical Operations and Research Office, National Aeronautics and Space Administration, John F. Kennedy Space Center, Florida, March 1986.

[13]Prince, R.P. and W.M. Knott. Plant growth chamber 'M' design. MacElroy, R.D., N.V. Martello, and D.T. Smernoff, (eds.) Controlled Ecological Life Support Systems: CELSS '85. NASA Ames Research Center, NASA TM-88215, 1986.

[14]Prince, R.P. and W.M. Knott. CELSS Breadboard Project at the Kennedy Space Center. Ming, D.W. and D.L. Henninger (eds.) Lunar base agriculture: soils for plant growth. Amer. Soc. of Agron., Inc. Madison, WI, 1989.

[15]Wheeler, R.M., J.H. Drese, and J.C. Sager. Atmospheric leakage and condensate production in NASA's Biomass Production Chamber. Effect of diurnal temperature cycles. NASA Tech. Memorandum 103819, 1991.

[16]Prince, R.P., W.M. Knott, J.C. Sager and J.D. Jones. Engineering Verification of the Biomass Production Chamber. *Proceedings of The 2nd Conference on Lunar Bases and Space Activities, the Lunar and Planetary Institute*, 1992, Pp 537-542.

[17]Wheeler, R.M., C.L. Mackowiak, W.L. Berry, G.W. Stutte, N.C. Yorio, L.M. Ruffe, and J.C. Sager. Nutrient, acid, and water budgets of hydroponically grown crops. Acta Horticulturae 481:655-661, 1999.

[18]Wheeler, R.M., J.H. Drese, and J.C. Sager. Atmospheric leakage and condensate production in NASA's Biomass Production Chamber. Effect of diurnal temperature cycles. NASA TM-103819. 1991.

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

[20]Wheeler, R.M. Gas-exchange measurements using a large, closed plant growth chamber. *HortSci.* 27: 777-780, 1992.

[21]Sager, J.C., C.R. Hargrove, R.P Prince, and W.M. Knott. CELSS atmospheric control system. *Amer. Soc. Agr. Eng. Paper* 88-401 8, St. Joseph, Michigan, 1988.

[22]Wheeler, R.M., C.L. Mackowiak, J.C. Sager, W.M. Knott, and C.R. Hinkle. Potato growth and yield using nutrient film technique. *Amer. Potato J.* 673177-187, 1990.

[23]Wheeler, R.M., C.L. Mackowiak, G.W. Stutte, N.C. Yorio, L.M. Ruffe, J.C. Sager, R.P. Prince, and W.M. Knott. Crop productivities and radiation use efficiencies for bioregenerative life support. *Adv. Space Res.* 41:706-713, 2008.

[24]Norman, J.M. and T.J. Arkebauer. Predicting canopy photosynthesis and light-use efficiency from leaf characteristics. Boote, K.J. and R.S. Loomis (eds.) *Modeling crop photosynthesis-From biochemistry to canopy.* Crop Sci. Soc. Amer. Madison, WI, 1991, pp. 75-94.

[25]Sinclair, T.R. Canopy carbon assimilation and crop radiation-use efficiency dependence on leaf nitrogen content. Boote, K.J. and R.S. Loomis (eds.) *Modeling crop photosynthesis-From biochemistry to canopy.* Crop Sci. Soc. Amer. Madison, WI, 1991, pp. 95-107.

[26]Batten, J.H., B.V. Peterson, E. Berdis, and R.M. Wheeler. Biomass production chamber air analysis of wheat study (BWT931). NASA TM-109192, 1993.

[27]Burton, W.G. The response of the potato plant and tuber to temperature. Rees, A.R., K.E. Cockshull, D.W. Hand, and R.G. Hurd (eds.) *Crop processes in controlled environments.*, Academic Press, London, 1972.

[28]Mackowiak, C.L, L.P. Owens, C.R. Hinkle, and R.P. Prince. Continuous hydroponic wheat production using a recirculating system. NASA TM-102784. 1989.

[29]Stutte, G.W., C.L. Mackowiak, N.C. Yorio, and R.M. Wheeler. Theoretical and practical considerations of staggered crop production in a BLSS. *Life Support and Biosphere Sci.* 6:287-291, 1999.

[30]Wheeler, R.M., G.W. Stutte, C.L. Mackowiak, N.C. Yorio, and L.M. Ruffe. Accumulation of possible potato tuber-inducing factor in continuous use recirculating NFT systems. *HortSci.* 30:790 (#262), 1995.

[31]Stutte, G.W. and N.C. Yorio. Biological activity of a vegetative and tuber growth regulator obtained from recirculating hydroponics. *Proc. Plant Growth Regulation Soc. Amer.* 1998, pp. 179-180.