ENGINEERING VERIFICATION OF THE BIOMASS PRODUCTION CHAMBER

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The requirements for life support systems, both biological and physical-chemical, for long-term human attended space missions are under serious study throughout NASA. The J. F. Kennedy Space Center "breadboard" project has focused on biomass production using higher plants for atmospheric regeneration and food production in a special biomass production chamber. This chamber is designed to provide information on food crop growth rate, contaminants in the chamber that alter plant growth, requirements for atmospheric regeneration, carbon dioxide consumption, oxygen production, and water utilization. The shape and size, mass, and energy requirements in relation to the overall integrity of the biomass production chamber are under constant study.

INTRODUCTION

The need to regenerate cabin atmosphere and water has been recognized by *MacElroy and Bredt* (1984) and *Gitel'zon* (1977). Until recently physical-chemical processes have been considered the most appropriate candidates for processing the life support resources. The use of higher plants in the recycling system was reported by *Gitel'zon et al.* (1975) and they indicated a reasonable measure of success. Based on a number of NASA studies, *Sweet and Tremor* (1978) asked for suggestions on the design of a chamber for higher plants. Other unrelated work by *Reid et al.* (1977) outlined a control system suitable to manage a plant growth chamber over a wide range of environments.

The Controlled Ecological Life Support System (CELSS) program managed by the Life Sciences Division of the Office of Space Science and Applications of the National Aeronautics and Space Administration (NASA) is committed to developing a system that provides basic life support requirements such as food, potable water, and breathable atmosphere for space crews on long-term space missions or extraterrestrial habitations. This program draws upon every aspect of the scientific community for information needed to accomplish a working CELSS and includes the utilization of research data accumulated over the past 16 years by an active grants research effort conducted under the CELSS program. To accomplish this biomass production, biomass processing, food preparation, product storage, atmospheric regeneration, waste management, crew habitation, analytical, and engineering and control are all required components.

In 1986 the Kennedy Space Center (KSC) began the "breadboard" project, which focused on a special biomass production chamber (BPC). This chamber was designed to function in a sealed (i.e., having an atmospheric leak rate of under 10% per day operating with an internal pressure of 12 mm H_2O above atmospheric) state while growing food crops. It was also designed to permit water and atmospheric contaminants to be collected and analyzed while growing different food crops and combinations of food crops. Physical and biological data combined will permit improvements to be made in the BPC and a more deliberate design of future plant growth chambers.

The term "verification" implies conformity with a truth or accuracy of a fact. It also signals a test of a theory or an examination of conformity to a standard. To physically verify the BPC requires a knowledge of the surrounding atmosphere, operating requirements, and cultural practices. To verify the crop growth needed will require an elaborate set of biological parameters. Another verification will involve the physical-biological interface. This has to do with those pieces (mostly physical) required to maintain integrity of any biomass production that might be suitable for microgravity environment. Since this BPC is designated as part of a breadboard project, changes in its operational mode, physical appearance, performance requirements and surroundings can and will be made as necessary.

Standards exist for maintaining the atmospheric seal of a spacecraft in a microgravity environment for a given period of time. Standards for measuring physical environmental parameters required to grow higher plants were edited by *Tibbitts and Koszlowski* (1979). *Tibbitts* (1984) also edited the NCR101 North Central Region Growth Chamber Committee quality assurance report for higher plant research conducted in growth chambers. Measurements on which to base certain biomass growth rates, contaminant levels, analytical monitoring, computer control algorithms, etc. have not been defined clearly. This paper will examine some of these issues and deal with a few processes in detail. The area of options will be examined in view of timeframes and assurances.

BIOMASS GROWTH REQUIREMENTS

Higher plant growth is regulated by physical and biological parameters. It is projected as a multidimensioned growth response phenomenon in which interactions between more than one parameter occur as shown in Fig. 1. Scientists have been

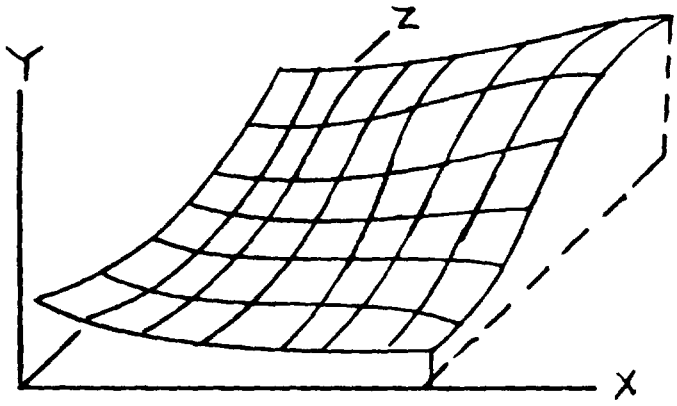

Fig. 1. A simplified view of a section of the nonuniform plant growth response surface.

investigating environmental parameters causing these growth responses. Some have endeavored to alter these environmental parameters to obtain higher energy transfer efficiencies, and have obtained success at finding the set of parameters to obtain high dry-matter yields of wheat (*Bugbee and Salisbury,* 1985, 1988). A better understanding of processes influencing this growth response is vital to the success of the CELSS effort.

The growth response surface may also be altered by mechanical or physical constraints such as the type of nutrient solution distribution systems, the plant support system, the volume needed in the root zone for root crops, the delivery systems used to supply oxygen to plant roots, etc. The use of an organic substrate tends to complicate nutrient delivery systems design from the standpoint of filtration and nutrient maintenance. The use of a nonabsorbing inorganic substance provides root anchor, increased volume, and added weight. An absorbing type of inorganic susbance also provides root anchor, increases system volume, adds weight, and complicates elemental balances within the nutrient system. For these reasons a thin-film continuous flow nutrient delivery system was designed for the KSC breadboard project.

This decision gave rise to whether a deep pool, thin-film, and continuous or intermittent flow would be the system of choice. A continuously flowing thin- (4-6-mm-deep) film type of nutrient delivery system was chosen since it might use less solution per plant, less total solution, and provide as good growth as other systems.

Nearly all the scientific data found in the literature were obtained without moving plants further apart as they grow to utilize radiation (light) more effectively and where an all-in-all-out planting-harvest scheme prevailed. Therefore, few scientific data are available for a given area where continuous cropping and plant spacing are practiced. Not all crops require spacing to maximize light utilization, but data on continuous cropping of a given area will be useful.

Table 1 gives the design requirements for the BPC. These requirements have been met in construction and now must withstand detailed evaluation. The monitoring and control ranges listed in Table 1 were considered adequate for the food crops being discussed for this ground-based test vessel. The crops are wheat, rice, soybean, bush beans, lettuce, sugar beets, sweet potatoes, white potatoes, peanuts, and tomatoes. We have grown

TABLE 1. Subsystem control and monitoring parameter requirements for the biomass production chamber (BPC).

Subsystem	Range for type
Heating, Ventilation, and Air Conditioning	
Controlled	
Air temperature	18-30°C
Relative humidity	60-70% RH
Ventilation rate	0.5-1 m sec^{-1}
Monitored	
Condensate water	400-500 l day^{-1}
Air filtration	99.9% at 0.3 μ
Gas and Pressure	
Controlled	
Oxygen	20.8%
Carbon dioxide	350-2500 μmol mol^{-1}
Chamber operating pressure	0.10-0.25 kPa
Radiation (Light)	
Controlled	
Radiation (light)	300-1000 μmol m^{-2} sec^{-1}
Photoperiod	0-24 hr
Nutrient Delivery	
Controlled	
Nutrient temperature	15-30°C
pH	5.5-6.5 pH
Conductivity	100-250 msm^{-1}
Flow rate	300 ml min^{-1} $tray^{-1}$

wheat, soybeans, bush beans, lettuce, and white potatoes to maturity in a commercial plant growth chamber using nutrient solution culture.

OTHER REQUIREMENTS FOR CROP GROWTH

Other factors that tend to influence plant response surfaces must be considered when evaluating the different components of a CELSS. Figure 2 shows a simplified way of looking at the different components. Within each component there may be many air, moisture, and people paths to control. Each must be evaluated and confirmed. Also, the components cannot function independently. For example, the system chosen for producing biomass will no doubt influence the waste management and biomass processing components. A much clearer picture can be drawn of the individual components and the total CELSS if many options are available.

While certain processes within the components of a CELSS may reach an ecological equilibirum, essentially every process, component, and the total CELSS will function on a real-time analytical analysis, process monitoring, and computer control system. Such control systems must be subject to the same verifications and options that prevail for other elements and components. Also there will exist a compromise, for the different activities may often conflict with biomass production. Further, it may be desirable to alter plant growth rate in order to accomplish certain outcomes.

VERIFICATION OF THE BPC

An existing steel vessel, 3.5 m in diameter by 7.5 m high, was modified to satisfy the previously mentioned BPC design requirements (Fig. 3). This modification consisted of installing 20 m^2 of shelf crop growing area on 4 levels for an area of

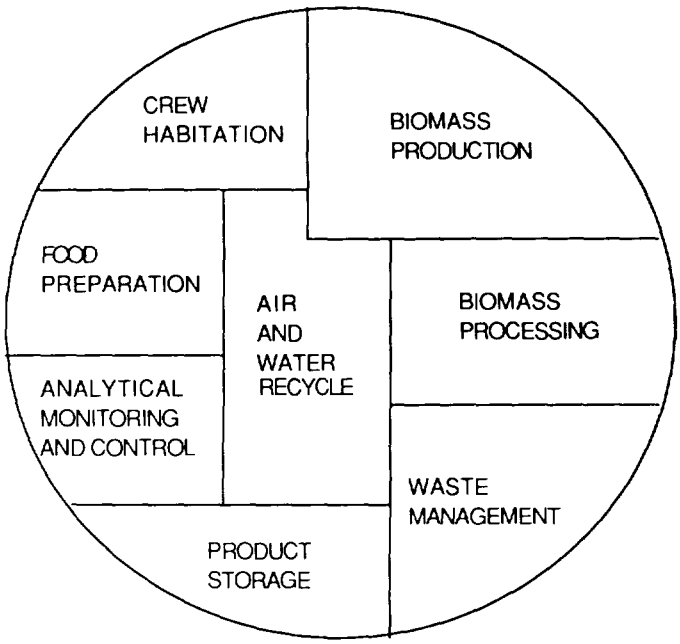

Fig. 2. A CELSS concept indicating air and water regeneration for all components and complete monitoring and computer control.

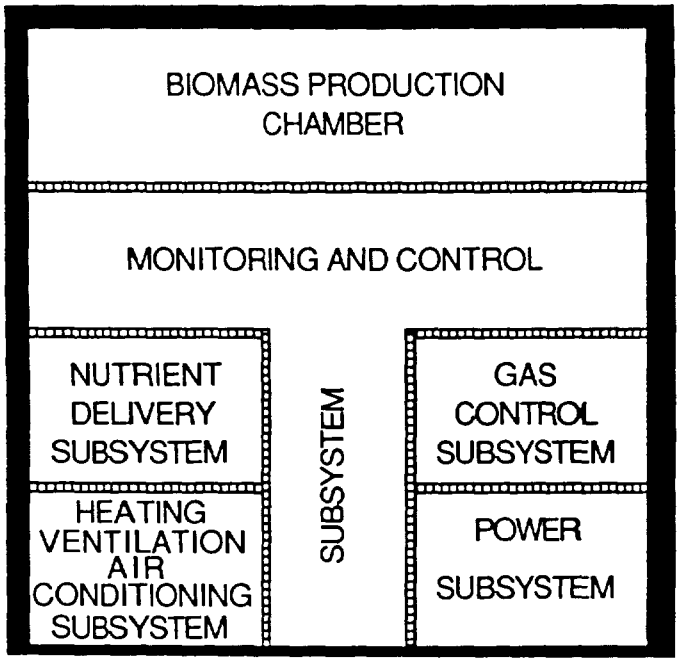

Fig. 3. Subsystem in place for maintaining and managing the biomass production chamber.

approximately 27 m^2 using 32 adjustable platforms. Above (approximately 1 m) each platform was mounted a lamp bank containing three 400-W high-pressure sodium (HPS) bulbs for a total of 96 bulbs. Eight lamp banks are located on each of the four growing levels. Two dimming controls are fitted to lamp banks on each level for a total of eight controls. Photosynthetic photon flux (PPF) can be computer controlled from 350 μmole m^{-2} sec^{-1} to 600 μmole m^{-2} sec^{-1} over the photosynthetic active radiation (PAR) waveband of 400 to 700 nm. All 96 lamp ballasts are located outside the chamber.

The stainless steel lamp banks were made with a Pyrex glass bottom and serve as a duct for air to pick up some lamp fixture heat as air returns to two air handling units. The time for one air cycle amounts to about 17 sec. Air enters the BPC beneath the lamp banks and above the plant canopy at a velocity of about 0.5 m sec^{-1}. During the air cycle temperature, relative humidity, and carbon dioxide are adjusted to preset levels. Oxygen (20.8%) and chamber pressure (12 mm H_2O above atmospheric) are maintained by releasing air or by the addition of breathing air. In addition to contaminant sampling inside the chamber, provisions were made in the duct system to sample supply and exhaust air.

An air handling unit (Fig. 4) consisting of a chilled water cooling coil, a hot water heating coil, a humidifier, an absolute filter, and a fan was in place for each of the two systems and served to direct the flow of air to and from the chamber. A 120-l stainless steel tank located beneath each cooling coil collected condensate water.

The nutrient delivery systems (Fig. 5) consisted of 64 isosceles-trapezoid-shaped plant growth trays, four 250-l nutrient reservoirs, plumbing, and fluid controls. Each tray contained its own plumbing and distribution header. The trays were constructed of polyvinyl chloride (PVC) and measured 25 mm deep by 432 mm wide at the wide end, by 178 m wide at the narrow end, by 0.84 m long, for an area of 0.25 m^2.

A tray top specifically designed for small grain consisted of a capillary plant support (CPS) larger than the one described by *Prince and Koontz* (1984) and is shown in Fig. 6. Approximately

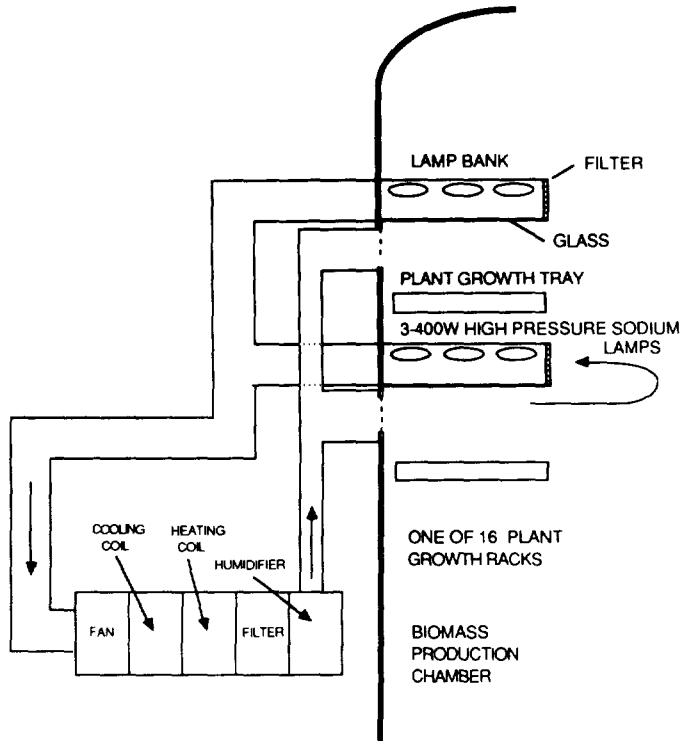

Fig. 4. Schematic of the heating, ventilating, and air conditioning subsystem.

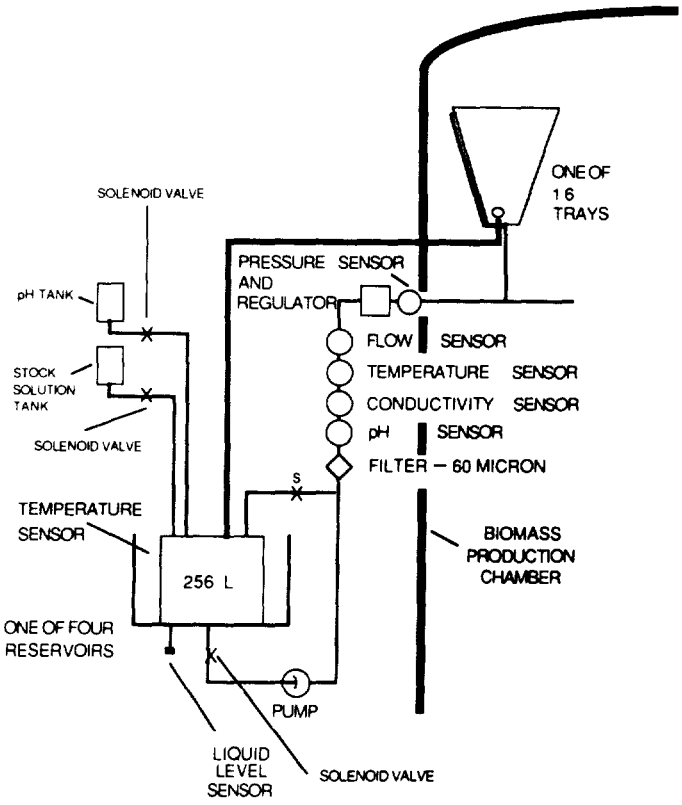

Fig. 5. Schematic of the nutrient delivery system.

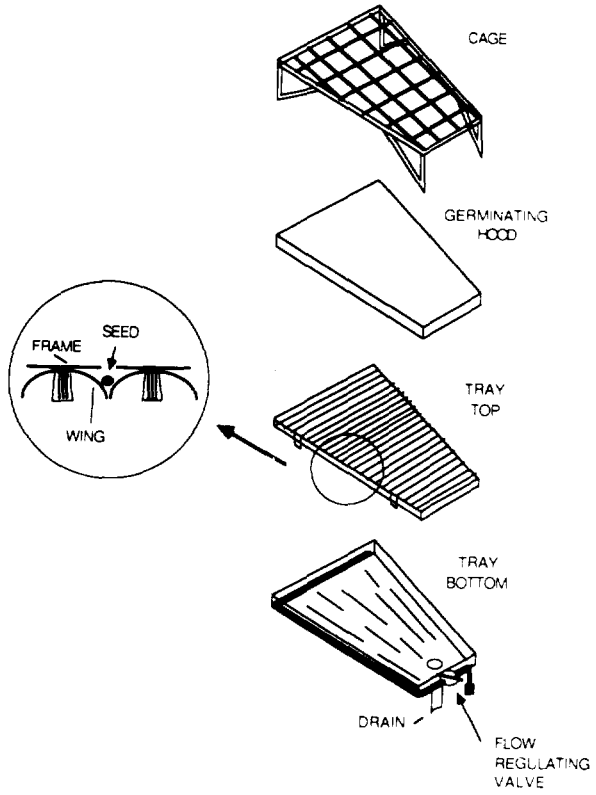

Fig. 6. Schematic of the capillary plant support (CPS) and the plant growth tray assembly.

TABLE 2. Physical and environmental parameters associated with biomass production chamber verification.

Physical		Environmental	
Parameter	Unit	Parameter	Unit
Ambient			
Total volume	m^3		
Leak rate	$l\ hr^{-1}$		
Positive pressure	mm H_2O	Relative humidity	%
Photosynthetic photon flux	$\mu mole\ m^{-2}\ sec^{-1}$ (400-700 nm)	Day Night	
Nonphotosynthetic shortwave radiation	700-2800 nm		
Longwave radiation	2800-100,000 nm	Partial pressure	Pa
Radiation source		Day	
Radiation filters		Night	
Barriers			
Lamp bank design		Carbon dioxide	$\mu mol\ mol^{-1}$
Photoperiod	hr	Day	
Temperature	°C	Night	
Day		Oxygen	%
Night		Day	
Air velocity through canopy	$m\ sec^{-1}$	Night	
Nutrient Solution			
Temperature	°C	Dissolved oxygen	%
Day		pH	
Night		Conductivity	$ms\ m^{-1}$
Condensate water	$l\ hr^{-1}$	Volume	m^3
Nutrient flow rate	$l\ sec^{-1}\ tray^{-1}$	Mass	kg

5.6 m of linear distance was provided for seed placement per tray. Up to 400 wheat seeds were used for yield studies. Once the seeds were in place, the germinating hood was placed on the tray. This hood contained a plastic screen underneath the top for the purpose of holding free water that would be evaporated over time, thereby maintaining a high relative humidity on the seeds and young seedlings. Following a 48-hr germinating period the hood was removed and a cage to keep the wheat upright at maturity was installed.

A control system utilizing sensors, control valves, switches, and a programmable logic controller (PLC) was installed. The PLC was programmed to maintain the environmental, liquid, and gas parameters within specified limits. It also managed alarms and arranged to shut down certain subsystems in the event out-of-range limits were reached. A separate set of sensors was installed for the specified purpose of monitoring all the parameters associated with chamber control and many parameters having to do with the particular experiment. The dataset consisted of 5-min storages of averages taken over 1-min intervals.

Evaluation of the degree of seal with respect to time and the total enclosed volume was made using the gas control and monitoring systems. This specification was met, as were the atmospheric temperature and relative humidity conditions. The nutrient delivery systems required fewer specific controls but more monitoring sensors. For all subsystems the control performace of the BPC without plants exceeded design specifications (Table 2).

VERIFICATION OF BIOMASS GROWTH

Lawlor (1987) explains photosynthesis as "the process by which organisms convert the energy of light into the chemical energy of organic molecules." He explains this process in terms of light (400 to 700 nm) energy, carbon dioxide, temperature, nutrition, and water. The biomass growth phenomenon as discussed earlier in this paper interacts with the verification process. Each and every new set of environmental parameters controlled to produce a crop may be used to verify growth (Table 3). Unfortunately, the dataset accompanying much of the early literature relating to crop growth in plant growth chambers did not contain all of the dataset we now need.

Detailed crop growth requirements were not a part of the BPC environmental requirements. To grow a respectable crop in a reasonable period of time yielding a considerable amount of edible biomass with little trouble was a satisfactory goal. Specific inputs over given time periods using certain cultural practices in a controlled environment should result in a certain edible biomass yield according to the literature for specified crops. The impact of a sealed chamber atmosphere on crop growth was a relative unknown. In recent times, however, commercial chambers have become much higher in atmospheric seal, giving confidence that major problems will not be encountered.

Using information from the literature and trials conducted at KSC in commercial growth chambers, Table 3 was constructed to give a partial listing of parameters needed and tasks to be accomplished to verify biomass growth. By collecting such data and making broad comparisons with similar commercial growth chamber data, it should be possible to evaluate crop growth and production. In all cases the dataset must contain descriptive details of cultural practices, nutrient maintenance methods, and environmental changes that occurred.

TABLE 3. Biological parameters and measurements associated with verifying biomass production chamber parameters.

Parameter	Unit	Parameter	Unit
Crop		Cropping System	
Variety		All-in-all-out	
		Continuous	
Seed storage		Interval	
Time		Spacing	
Temperature	°C	Other†	
Moisture	% RH	Plant support‡	
Controlled			
Atmosphere			
Propagation*		Plant, Nutrition	
Seed		N	mm
Cell culture transplant		P	mm
		K	mm
		Ca	mm
		Mg	μm
		S	μm
		Fe	μm
		Mn	μm
		Zn	μm
		Cu	μm
		B	μm
		Mo	μm
		Cl	μm
Germination	%	Nutrient maintenance§	
Survival	%	Conductivity	
Plant density	Plants m^{-2}	On-line analysis	
Growth rate¶			
Height	mm	Volume**	m^3
Diameter	mm	Area††	m^2
Dry matter	g		
Photosynthetic rate¶	μmol m^{-2} sec^{-1}	Leaf area index††	
Harvest (dry weight)	g $plant^{-1}$		
Total biomass	gm^{-2}	Analysis - Biomass	
Edible biomass		Proximate	
Nonedible biomass		Chemical	
Shoot:shoot ratio			
Moisture content (wet weight)	%		

For the parameters indicated, an investigator must perform the following:
* A complete description of equipment needed and procedure used is required.
† Describe and depict the spacing system.
‡ Identify the complete plant holder, seed to harvest.
§ Describe in detail.
¶ Show graph with respect to time.
** Total plant volume, plants only.
†† Ratio of leaf area to the growing area, m m^{-1}.

It may be desirable to obtain a plant canopy as quickly as possible after planting for reasons of light utilization. For some crops this may be achieved by spacing the individual plants as they grow, thereby maintaining a somewhat uniform canopy. The cultural practice of spacing and moving was referred to by *Prince and Koontz* (1984) as "continuous production." In this procedure and where the scheduled time between harvesting and seeding is less than seven days, the term "crop growth rate" may be justified. In all cases the exact area and the days (seed to harvest), as well as the planting schedule, must be part of the dataset. Further, knowledge is lacking as to how to vary growth

rate in relation to oxygen demand and food needs. Such a system is important when considering limited oxygen storage, unplanned crew activity, and required waste management processes that may require oxygen. Utilization of carbon dioxide and water will also be changed. The influence of microbial activity, pathogens, and insects must become part of the verification process. Detection of changes in net photosynthesis and identification of cause will become important pieces of information for evaluation purposes.

SUMMARY

NASA KSC has designed and constructed a biomass production chamber as part of the breadboard project. It is 3.5 m in diameter by 7.5 m high, and the total biomass production area is 20 m^2 on four levels. A thin-film continuous-flow nutrient delivery system supplies water and nutrients to plant roots.

The chamber and the ability of plants to grow in the chamber are subject to verification. The chamber can be verified from a strict physical and environmental compliance standpoint. The flexibility in limits permitted must ultimately fall within the bounds of adequate biomass growth. Verification of biomass production is determined by dry matter for a particular set of environments and feedback algorithms.

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