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THE CROP GROWTH RESEARCH CHAMBER: A GROUND-BASED FACILITY FOR CELSS RESEARCH

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ABSTRACT. A ground-based facility for the study of plant growth and development under stringently controlled environments is being developed by the CELSS program at the Ames Research Center. Several Crop Growth Research Chambers (CGRC) and laboratory support equipment provide the core of this facility. The CGRC is a closed (sealed) system with separate recirculating atmosphere and nutrient delivery systems. Environmental influences on gas exchange, growth and development, and biomass and food production of crop plants growing within the closed environment will be investigated. Laboratory size of the CGRC will be small enough to allow treatment replication but large enough to provide information representative of larger plant communities. Water recovery and management systems and gas management systems will be included. Eventual integration of candidate waste processing technologies into the cycling system is intended.

Development of a Controlled Ecological Life Support System (CELSS) requires identification of the critical requirements that will allow the system to operate with stability and efficiency. Identifying and meeting those requirements will be accomplished through scientific experimentation and technology development on the ground. A Crop Growth Research Facility has been defined by CELSS principal investigators and science advisory panels as necessary for the development of a bioregenerative life support system (1,2).

The crop growth research facility is for the study of plant growth and development under stringently controlled environments isolated from the external environment. This facility is important for three CELSS activities: 1) research, 2) system control and integration, and 3) flight hardware design and experimentation. Several Crop Growth Research Chambers and laboratory support equipment provide the core of this facility. The Crop Growth Research Chamber (CGRC) is a closed (sealed) controlled environment system designed for the growth of a community of crop plants with separate recirculating atmosphere and nutrient delivery systems.

CGRC HISTORY

The CGRC concept was first discussed during a 1984 meeting at the Ames Research Center (ARC) attended by CELSS principal investigators and NASA scientists and engineers. The purpose of the meeting was to define requirements for the development of a CELSS. Equipment needed for research to be conducted on earth and in extraterrestrial environments was discussed. A need was identified for a plant growth chamber where crops could be subjected to ground-based verification of flight environments. Science requirements for chamber performance were developed (1). A design concept for a Plant Growth Module (PGM) was produced in 1985 based on those science requirements.

During 1984 and 1985 a decision was made to construct the Biomass Production Chamber (BPC) at the Kennedy Space Center with the purpose of scale-up and verification of crop production results from research laboratories. The verification goal for the BPC serves several important purposes in the CELSS program but the need for research in closed environments is not adequately addressed by that chamber.

CELSS principal investigators and NASA scientists met at ARC in 1986 to confirm the need for a research facility to investigate plant growth in systems isolated from the external environment. At this meeting a need was identified for a unique research facility to address topics in a manner not possible in the BPC. Emphasis was placed on the need for such a facility to have the capabilities for tightly sealing the plant growth chamber, having minimal exchange of mass with the external environment, and conduct experiments with appropriate replication and control treatments. The general feeling of the principal investigators was that a better facility would be built if all had input into the development of one facility rather than each building their own version with unique problems and with great cost. As a result, a CGRC Research Consortium was formed to act as an advisory panel during development of the research facility. The individual chambers were suggested to have the title Crop Growth Research Chamber to indicate the primary goal.

Requirements for a Space Station based unit capable of conducting CELSS experiments were defined at a workshop in 1987 (2). The group at the workshop, many of whom were members of the CGRC Research Consortium, agreed that the CGRC could and should serve as the developmental unit for flight prototype hardware and technology development.

By early 1988 the need for a controlled environment research facility for CELSS had been clearly stated. The CGRC had been identified as the individual unit where various combinations of environmental factors could be selected and the influence on biomass and food production of a community of crop plants investigated.

With the need of a crop growth research facility identified, and the research priority in design specifications clearly stated, in March of 1988 Ames scientists and engineers formed a working group to define the personnel and facility needs for CGRC development. The scientists of the group represented the needs for ground-based and in-flight CELSS research, the engineers represented the design, mechanical, and electrical engineering disciplines.

In June of 1988 the ARC science and engineering working group met with the CGRC Research Consortium to further develop and achieve consensus on the science requirements for the CGRC. There was a general discussion of the research efforts required for CELSS development and each principal investigator discussed their unique desires for potential utilization and application of the CGRC. The meeting was very informative and was particularly effective in exposing the engineers to the wide range of applications of the CGRC and the necessity for strict environmental control. After reviewing the science requirements the ARC working group defined the personnel needs for CGRC design and development, and so in October of 1988 the ARC Engineering and Science Team for CGRC development was assembled.

The tasks assigned to the CGRC engineering and science team were to, 1) develop clear understanding of science requirements, 2) develop and produce an engineering requirements and specifications document, 3) begin system and subsystem conceptual design, and 4) meet with the CGRC Research Consortium and controlled environment engineers to review the engineering requirements document and first level system/subsystem conceptual design.

The engineering and science team has utilized the CGRC science requirements (task 1) to develop and complete the "Crop Growth Research Chamber Requirements Specification" (task 2) (3). This engineering specification document is now being used to direct system and subsystem design (task 3). A series of engineering review panels within ARC will evaluate conceptual designs with CGRC Research Consortium and controlled environment engineers review of preliminary designs to follow (task 4). Completion of the final design and review process will lead to fabrication of a CGRC prototype. This prototype will then be subjected to a series of tests to evaluate performance and verify that design goals have been accomplished. Following verification of CGRC prototype performance several units will be constructed and integrated with laboratory and analytical equipment at ARC to make up the Crop Growth Research Facility.

CGRC OBJECTIVES

Objectives of CGRC use can be separated according to three areas of application: 1) research, 2) system control and integration, and 3) flight hardware design and experimentation. In reality, however, all work conducted in the Crop Growth Research Facility will have application to CELSS development. Work will be conducted to define the production efficiency of human usable products per unit input to the system and to define the hardware performance requirements for a CELSS in extraterrestrial environments. As mission scenarios are developed with clearly defined input limitations constrained optimization can be performed using the information acquired in the Crop Growth Research Facility to choose the optimum system design.

Research - The laboratory size of the CGRC will be small enough to allow duplication of the unit, treatment replication, and conduct of controlled experiments, but large enough to provide information representative of larger plant communities. An important feature for research is that the CGRC be of manageable size so that tasks can be performed in a timely fashion. Single plant chambers are potentially the easiest system to manage but we know that single plant growth is not an adequate nor acceptable indicator of community performance (4,5).

The CGRC will provide a range of environments not available to individual CELSS investigators in the form of unique or commercially available equipment. The CGRC represents the next generation of controlled environments. Capabilities include the potential for uninterrupted photosynthetic photon flux levels of 3000 μmol m^{-2} s^{-1} or greater (full noon sun is approximately 2000 μmol m^{-2} s^{-1}) and "closure" so that mass within the chamber is conserved. The CGRC will provide the capability for manipulation and control of atmospheric constituents allowing the study of individual and interactive effects on gas exchange and biomass and food production of plants. Closure of the system will allow identification of plant produced volatiles and soluble organics. Quantification of the effects of volatile and soluble organic compounds and trace gas contamination on crop performance will be possible. Microbial population dynamics and pathogen challenge to the system are intended applications of the CGRC.

System Control and Integration - Operation and control of a stable system is essential for development of a reliable life support system. The crop growth unit is only one portion of a CELSS but the crop plants function as several unique component processors. Carbon dioxide is removed from the atmosphere while oxygen is introduced through photosynthesis. Plant transpired water has been filtered through uptake by the root and incorporation of solutes into tissue before being evaporated from the interior of stomata of the leaves to the atmosphere. Transpiration rate can be manipulated over a wide range by environmental conditions. Carbon dioxide utilization and oxygen and water production are dynamic systems with short response times and the rate at which these processes operate can be varied as needs for a particular product vary. Of course food is being produced by the plants at the same time; the response time for expression of perturbations in the food production process is much greater than that observed for the other plants processes.

Edible plant yield is the integration of development during several unique phases between germination and harvest. Understanding the dynamics of yield development, i.e. having knowledge of crop responses to environmental manipulation during yield critical phases, is essential to predicting system performance.

Carbon dioxide uptake, and oxygen, water, and food can all be considered as products of the plant component of a CELSS. Information required for trade-off analysis to determine the short- and long-term gains and losses resulting from environmental manipulation during the life cycle of a crop as required for the desired plant product will be provided by the Crop Growth Research Facility.

Future interface with candidate unit processors on a laboratory scale will be possible. As candidate processes are developed for such operations as waste processing, oxygen removal and storage, nutrient recycle, and harvest and food processing, laboratory scale prototype units could be interfaced with the CGRC. Performance of these processors and requirements for interface with a crop growing unit could be evaluated. Unacceptable processors or designs could be discarded before the time and expense is expended on scale-up and interface with the Biomass Production Chamber (BPC) at the Kennedy Space Center.

Ames Research Center was recently assigned as lead center for the physical chemical/closed loop life support system (PC/CLSS) program activities. The CELSS and PC/CLSS groups have been organized into one life support program in the Life Science Division. Since CELSS includes the appropriate physico-chemical processors we are now in a unique position to develop technology necessary for a truly regenerative life support system.

Mathematical models are important to CELSS for prediction of biomass, food, water, and oxygen production and CO_2 consumption by the crop plants, integration of biological and physico-chemical subsystems, and implementation of control theory. The Crop Growth Research Facility will supply information required for model development and will provide the vehicle for model validation.

Control in a CELSS will not be a trivial matter. The fully functional extraterrestrial CELSS, as well as the ground-based research and breadboard CELSS projects, represent very complex and dynamic systems with processes that can be varied. The CGRC is being utilized as a test bed for control theory application and verification (6).

Flight Hardware Design and Experimentation - The CGRC serves as the mechanism for setting science and engineering specifications, technology assessment, and potentially serves as the ground-based control unit or reference for the CELSS Test Facility of the Space Station Freedom. The CGRC science requirements for performance and the CGRC Engineering Specifications Requirements document (3) are being utilized for development of the CELSS Test Facility (CTF) and for estimation of system complexity, mass, volume, and cost.

THE CGRC SYSTEM

The CGRC system has two main components, the atmospheric environment and the hydroponic environment. Both environments must be maintained independent of the other; the goal is to have no movement or migration of materials between the environments except for what is conducted through the plants which are continuous between the environments.

Atmospheric Environment - The atmospheric environment has several component subsystems and physical zones as shown in Figure 1. The growing volume makes up the majority of the atmospheric environment. The shoot, root, and subroot zones are included in the growing volume. The root zone, while located within the growing volume is a component of the hydroponic environment. The shoot zone is the area above the root zone. The size of the shoot zone will vary as the the plants are raised or lowered as required for experimental treatment or as the plants increase in size. The subroot zone is a very small volume which accommodates the flexible tubing and connections for the hydroponic system. The subroot zone is a very small volume when the root zone is in the lowest position and the shoot zone is near maximum volume.

Located external to the growing volume are the gas makeup system, heating/cooling/ventilation system, pressure control system, gas removal and separation system, lamp system, hydroponic reservoir, water condensation and collection system, and the associated ducting. The entire atmospheric system will be sealed to minimize leaks and the system will be positively pressured throughout.

Photosynthetically active radiation will be supplied to the growing volume by a lamp system located external to the closed atmospheric environment. A transparent barrier placed between lamps and plants will maintain the seal while minimizing the amount of non-photosynthetically active radiation entering the growing volume (7).

The recirculating hydroponic solution in the root zone will remain isolated from the gaseous atmosphere of the shoot zone. Water will be conducted from the root zone by the plant and enter the shoot zone by transpiration. Transpired water will be collected for analysis and eventually recycled to the hydroponic or the humidification systems.

Hydroponic Environment - The hydroponic system will supply a source of temperature controlled and oxygenated nutrient solution to the plant roots. The composition of the solution will be monitored and controlled. CGRC operation in the facility will allow a common solution to be circulated in all CGRCs or several experimental solutions to be circulated among representative solution containers in each CGRC.

System Control and Data Acquisition - All systems must function in concert to maintain control, within tight tolerance, the settings for all environmental parameters. While the CGRC is made up of several subsystems and components, it is itself an analytical research instrument which must function as designed with stability and repeatability. Measurements made within the chamber will serve as feedback to the control system and as scientific data that will be further utilized in calculations and manipulations. The control system and data acquisition systems may physically be the same system with redundant sensor placement or each system may be unique.

CGRC SCIENCE REQUIREMENTS

For the Crop Growth Research Facility to be able to accomplish the stated goals each individual unit in the facility must be capable of providing a wide range of environmental conditions to accommodate the studies to be conducted. A set of science requirements, better referred to as hardware performance requirements, for the CGRC were determined by the CGRC Research Consortium (Table 1).

The functional design in figure 2 represents the processes necessary to accomplish the performance requirements of the CGRC. System component characteristics will be determined during the design process. A potential physical appearance of the CGRC is portrayed in figure 3.

SUMMARY

The Crop Growth Research Chamber represents a unique controlled environment research and developmental tool available to the CELSS program. The integration of several CGRCs and laboratory analytical equipment provides a facility useful for ground-based and flight research, technology development, CELSS component subsystem integration, and system control. The Crop Growth Research Facility will allow evaluation of the stability of a CELSS and determination of the quality of the human useable products.

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Table 1. Crop Growth Research Chamber Science Requirements for Environmental Control.

Parameter	Control Range	Accuracy
Air Temperature	5-40°C	±1°C
Air Pressure	+ 15 mm H_2O(gage)	± 5 mm H_2O(gage)
Relative Humidity	35-90%	± 2%
Air Composition		
Nitrogen	75-95%	± 5%
Oxygen	5-25%	± 5%
Carbon Dioxide	25-5000 μmol mol^{-1}	± 0.2%
Air Flow Rate	0.1-1.0 m s^{-1}	± 0.1 m s^{-1}
Photosynthetic Photon Flux	0-3000 μmol m^{-2} s^{-1}	± 2%

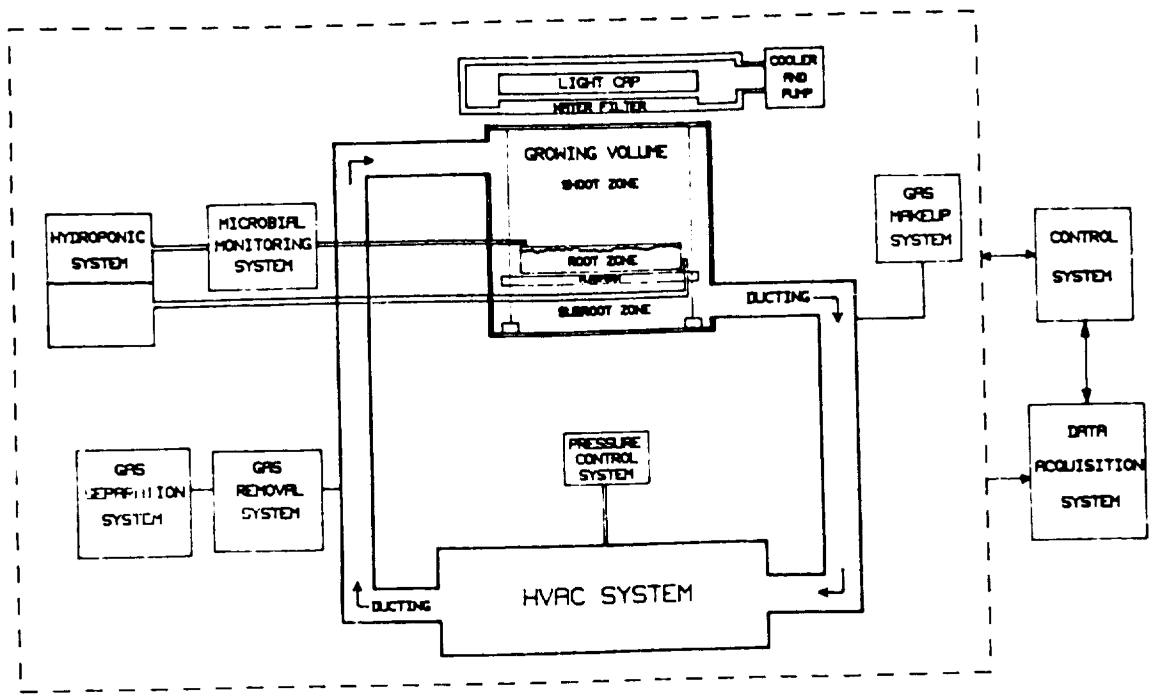

Figure 1. Block diagram of component subsystems and physical zones of the Crop Growth Research Chamber (CGRC).

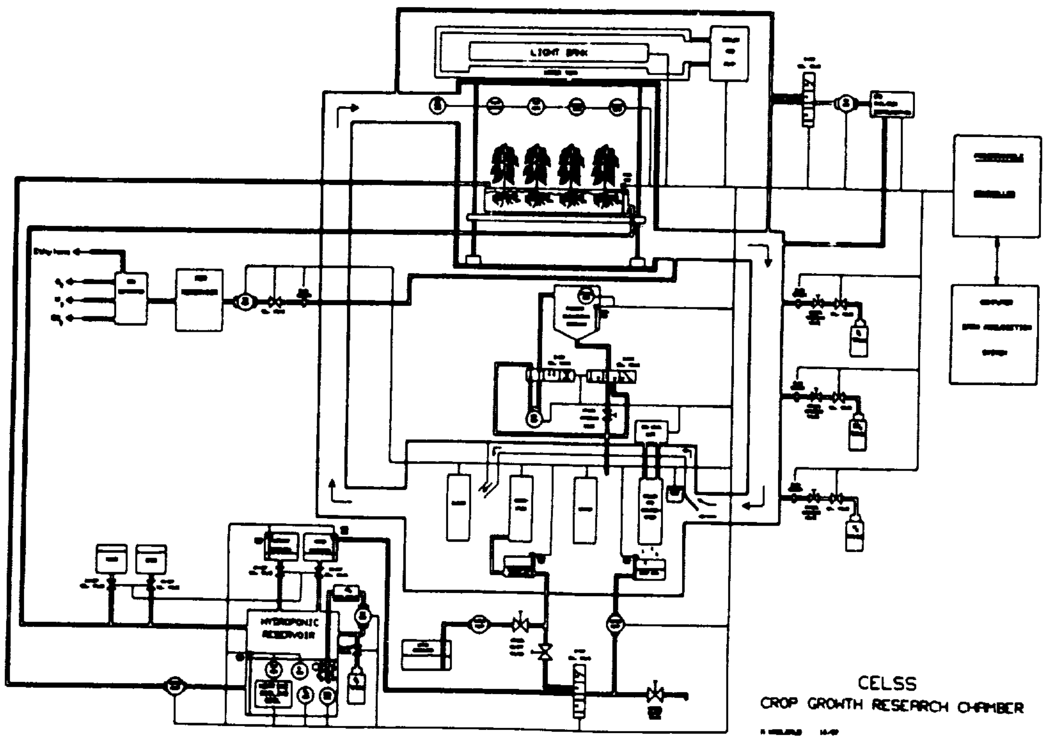

Figure 2. Functional design of the Crop Growth Research Chamber.

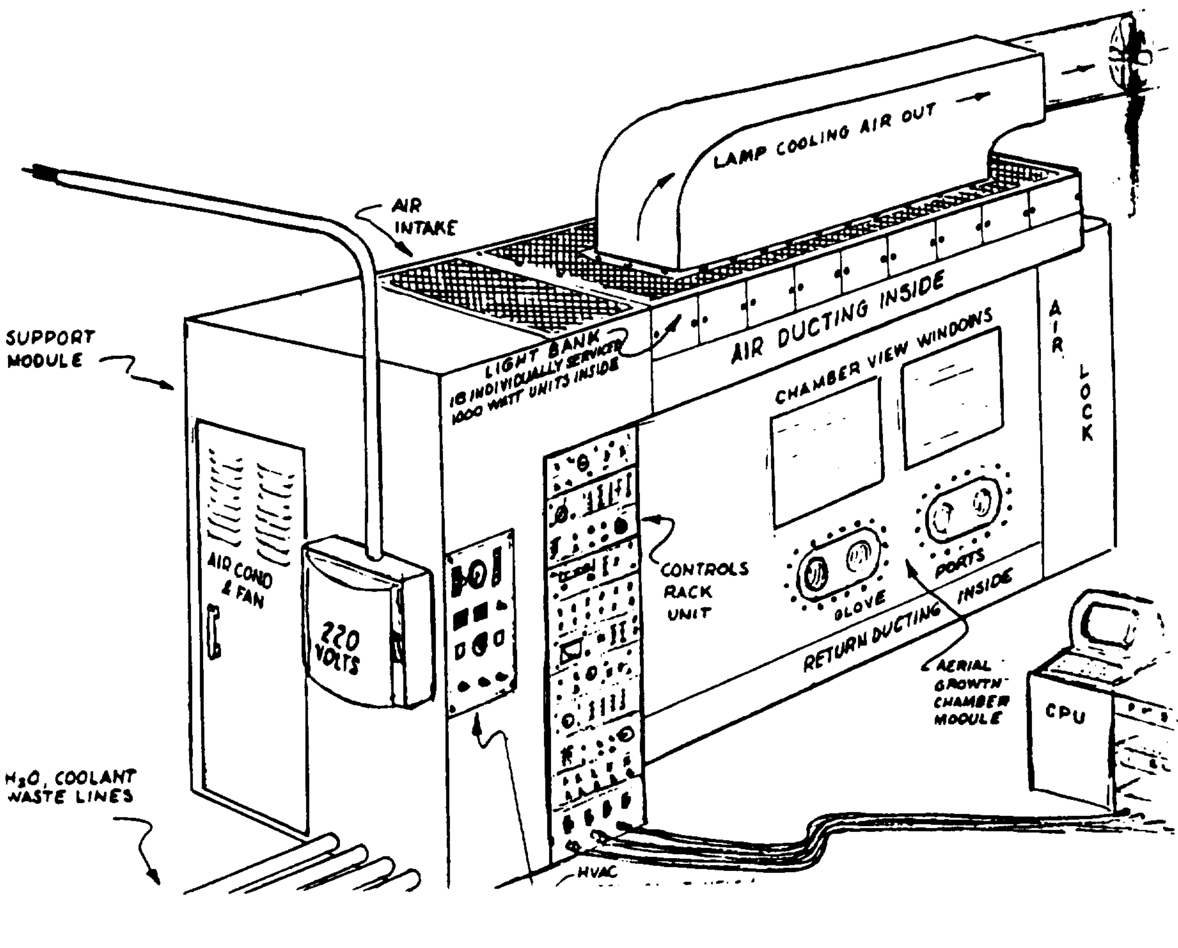

Figure 3. Potential physical appearance of the Crop Growth Research Chamber.