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THE CROP GROWTH RESEARCH CHAMBER

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INTRODUCTION

In order to support humans on a Lunar base or a mission to Mars, the essential elements for life support, namely water, food, and oxygen, must be supplied. The Controlled Ecological Life Support System (CELSS) program defines a regenerative life support system which supplies these elements with a minimum of resupply and waste. The primary goal of the CELSS program is to provide the major components of life support in a closed system which operates with stability and efficiency. The conceptual diagram of a CELSS is shown in figure 1. The figure focuses on the four major components of the closed system, (1) biomass production or plants, (2) food processing, (3) humans, and (4) waste processing, and how materials and gases flow from one component to another. The next step of identifying and meeting the detailed requirements of the CELSS system will be accomplished through scientific experimentation and technology development in space and on the ground.
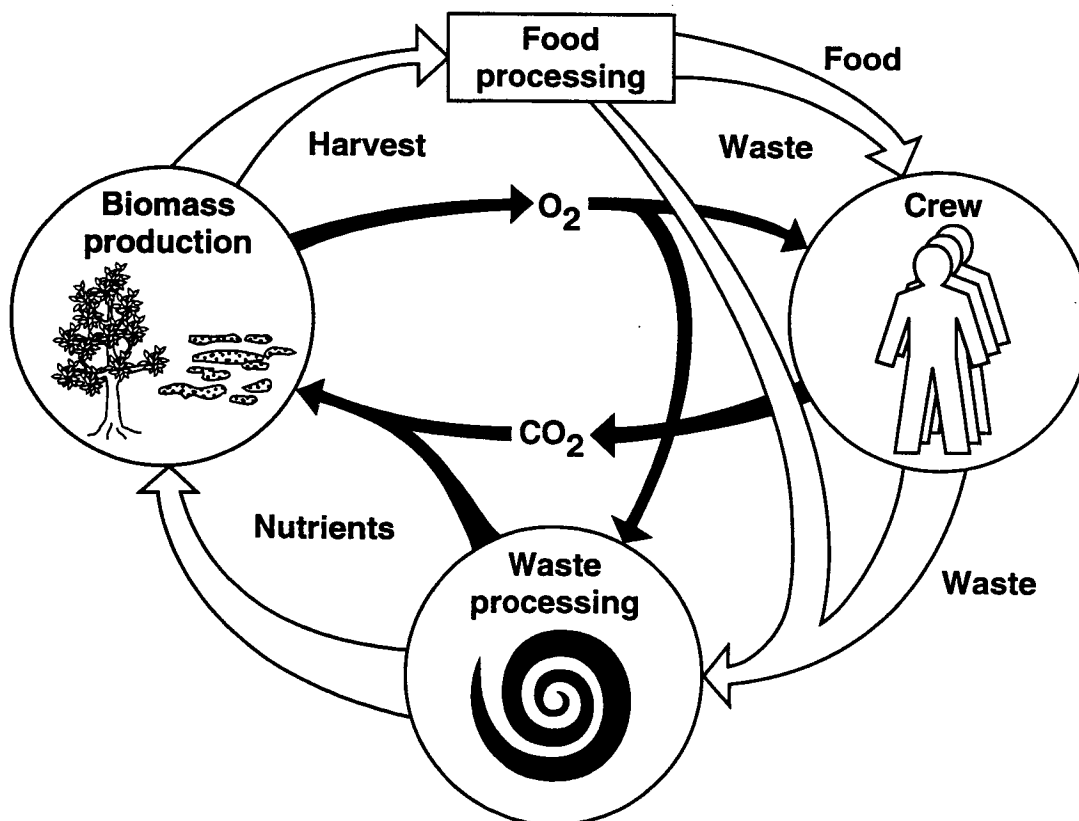

Figure 1. Conceptual diagram of a CELSS.

The Crop Growth Research Chamber (CGRC) has been defined by CELSS principal investigators and science advisory panels as a necessary ground-based tool in the development of a regenerative life support system (refs. 1 and 2). The focus of CGRC research will be on the biomass production component of the CELSS system.

The ground-based Crop Growth Research Chamber is for the study of plant growth and development under stringently controlled environments isolated from the external environment. The chamber has importance in three areas of CELSS activities: (1) crop research, (2) system control and integration, and (3) flight hardware design and experimentation. The laboratory size of the Crop Growth Research Chamber will be small enough to allow duplication of the unit, conduct of controlled experiments, and replication of experiments, but large enough to provide information representative of larger plant communities. Experiments will focus on plant growth in a wide variety of environments and the effects of those environments on plant production of food, water, oxygen, toxins and microbes. To study these effects in a closed system, tight control of the environment is necessary.

CROP GROWTH RESEARCH CHAMBER DESCRIPTION

The CGRC is a closed (sealed) controlled environment system designed for the growth of a community of crop plants with separate, recirculating atmospheric and nutrient delivery systems. In the CGRC, various combinations of environmental factors can be selected and the influence on biomass, food, water, and oxygen production of crop plants investigated. Also, measurement of plant produced toxins and microbial activity will be performed to determine if control of these elements will be necessary in a CELSS. Strict environmental control, closure or sealing of the system, and conservation of mass in the system are essential to measure the effects of various environments on crop production rates.

The CGRC is unique in that it will provide environmental control of more parameters over wider ranges and with higher accuracies than any other closed plant growth chamber. It will also take the next step in gas control by monitoring and selectively removing constituent gases as necessary to maintain setpoints. Table 1 details the CGRC control variables, their ranges and accuracies.

As shown under the physical specifications, the maximum allowable leak rate is extremely low. It can be achieved theoretically, however, the challenge occurs when purchasing off-the-shelf components such as motors, heaters, and compressors to maintain this level of closure. Also, the ratio of the growing volume to the total air volume is required to be at least 30%. This requirement stems from the necessity to measure toxins produced by the plants. If the growing volume is much smaller than 30% of the total air volume, small amounts of toxins produced by the plants will be diluted and may not be measurable.

A simplified block diagram of the CGRC is shown in figure 2. Each system is shown as a block and will be described in the following paragraphs. The sealed portion, commonly called the chamber, includes the growing volume, the ducting, and the air-conditioning system. The other systems are located external to the chamber and are interfaced to the chamber through ports located

Table 1: Design parameters table 2

Physical specifications	Limits	
1. Closure		
a. Leak Rate	$< 0.5\%$ of total CGRC air volume day^{-1}	
2. Size		
a. Total Air Volume	15 m^3	
b. Growing Volume	$> 30\%$ of total CGRC air volume	
c. Growing Area	≈ 2.0 m^2	

Environmental Control	Control Range	Control Accuracy
1. Shoot Zone		
a. **Air Temperature**	**15-40°C**	**±1°C**
b. Air Pressure	±108 kPa (absolute)	±1.6 kPa
c. **Relative Humidity**	**35-90%**	**±3% RH**
d. Air Composition		
Nitrogen	750-950 mmol mol^{-1}	±1.6-2.7 mmol mol^{-1} [a]
Oxygen	50-250 mmol mol-$^{-1}$	±1.5-2.5 mmol mol^{-1} [a]
Carbon Dioxide	25-50k µmol mol^{-1}	± 5-500 µmol mol^{-1} [a]
e. **Air Velocity**	**0.3-1.0 m s^{-1}**	**±10%**
f. **Photosynthetic Photon Flux**	**0%, 30%-100%**	**±15%**
2. Nutrient Solution in Hydroponic Reservoir		
a. Temperature	15-40°C	±1°C
b. pH	4.0-8.0	±0.1 units
c. Conductivity	50-500 mS m^{-1}	±10 mS m^{-1}
d. Oxygen Concentration	5-20 µmol mol^{-1}	±0.5 µmol mol^{-1}

[a]Measured accuracy.

Tested using the Engineering Development Unit

on the chamber walls. Even though these systems are physically external to the chamber, they maintain closure.

The growing volume includes the shoot zone where the plant shoots grow, the root zone where the plant roots grow in a hydroponic solution, and the subroot zone where the hydroponic nutrient delivery system piping is housed. The shoot zone and the root zone are separated with a medium located at the base of the plant stem, providing isolation of the shoot from the root 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. Separation of the shoot zone from the root zone is necessary for accurate measurement of plant transpiration, carbon dioxide uptake, oxygen production, and toxin production in the shoot zone, and microbial monitoring and nutrient usage in the root zone. Environmental parameters controlled in the growing volume include air temperature, chamber pressure, relative humidity, air composition, air velocity, and lighting (photosynthetic photon flux).
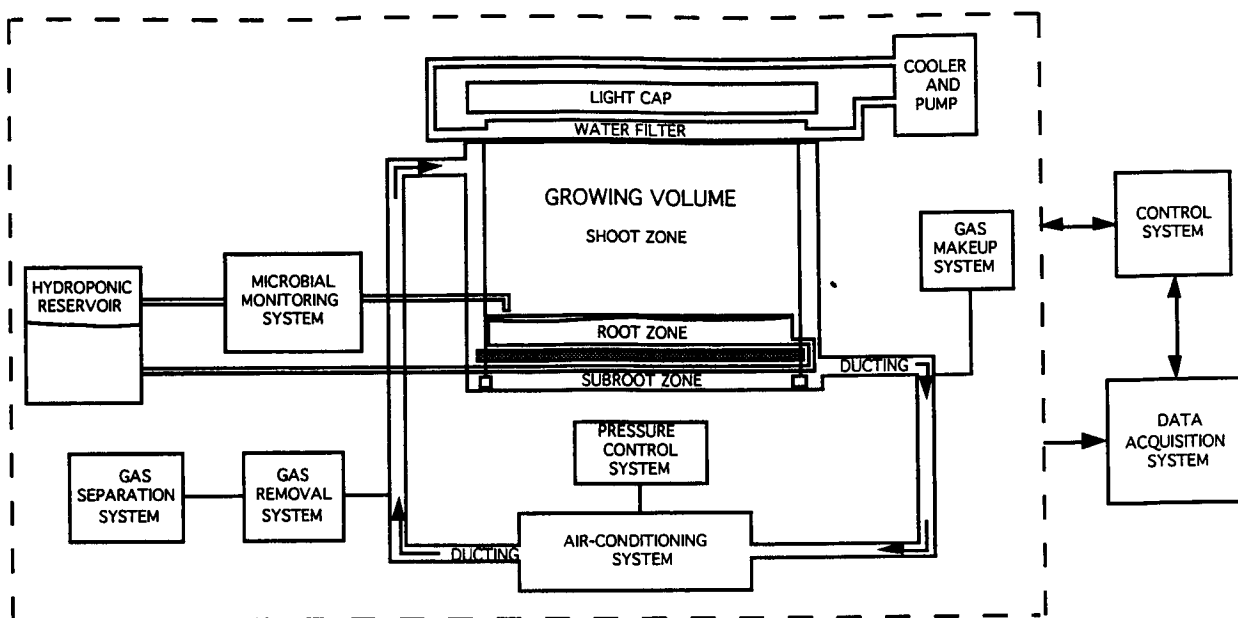
Figure 2. The crop growth research chamber block diagram.

Parameters controlled in the hydroponic reservoir which feeds up to 3 different nutrient solutions to the root zone are solution temperature, pH, conductivity, and oxygen concentration.

The air from the growing volume is transported through the ducting to the air-conditioning system which controls temperature, relative humidity, and velocity. The pressure control system port is located in the air-conditioning system and upstream of the gas removal and separation systems, to allow any air that enters the airstream from the pressure control system to be conditioned prior to entering the growing volume.

The light cap houses sixteen, 1000 watt, high-pressure sodium lamps which provide photosynthetically active radiation (wavelength = 400-700 nanometers) required for photosynthesis. The water filter located directly below the lamps consists of temperature controlled water flowing on the glass ceiling of the chamber. The water and glass filter out the longwave radiation to reduce the heat input to the chamber and to maximize the percentage of energy input that is photosynthetically active. A hood covering the light cap is required to prevent extraneous light from entering the chamber since only radiation from the overhead lamps can enter the chamber.

The gas makeup, removal and separation systems control the levels of nitrogen, carbon dioxide and oxygen within the chamber by selectively removing or injecting constituent gases. The gases removed and injected are quantified in order to determine how much of each gas is consumed or produced by a particular crop under pre-determined environments.

The hydroponic reservoir contains the nutrient solution which is fed to 10 plant trays located in the root zone. Three different solutions will be available to feed to the 10 trays to allow for random testing of various nutrient solutions. The control of the solutions' compositions is automated and recorded to determine the uptake rates of various chemicals by the plants.

The control and data acquisition systems allow for control of all the parameters listed in table 1 as is shown by the dotted lines encompassing the systems in figure 2. 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 to investigate trends in the various parameters.

Not only is the design of each separate system technically challenging, but the integration and control of the system as a whole makes the CGRC the first of its kind.

ENGINEERING DEVELOPMENT UNIT

A Science Advisory Review for the Crop Growth Research Chamber (CGRC) was held in February 1990 to review the preliminary designs. Due to discussions and concerns regarding the CGRC's air-conditioning system design and the need for control system hardware and software experimentation, it was decided to build an Engineering Development Unit (EDU). The main purpose for building the EDU was to test the hardware and software necessary to control temperature and relative humidity within the wide ranges and high accuracies listed in table 1. Therefore, the EDU includes only the air-conditioning system and control components necessary to control temperature and relative humidity. Closure was not a goal of the EDU, although steps were taken so closure could be simulated in order to accurately assess control.

A simplified diagram of the EDU is shown in figure 3. The variable speed fan is required to control the air velocity inside the chamber from 0.3 to 1.0 m s^{-1} ± 10%, as measured from the top plane of the plant canopy. The dampers determine the amount of airflow that is partitioned through the coil and through the bypass. They are controlled by the linear actuators. Most of the air flows through the bypass in cases when the plants are small and do not transpire heavily enough to require dehumidification of the air. In cases when the plants are large and transpire substantial amounts of water, most of the air is passed through the coil for dehumidification. The electric heater provides reheat for points on the envelope in which too much heat is extracted by the coil in order to obtain the correct relative humidity.
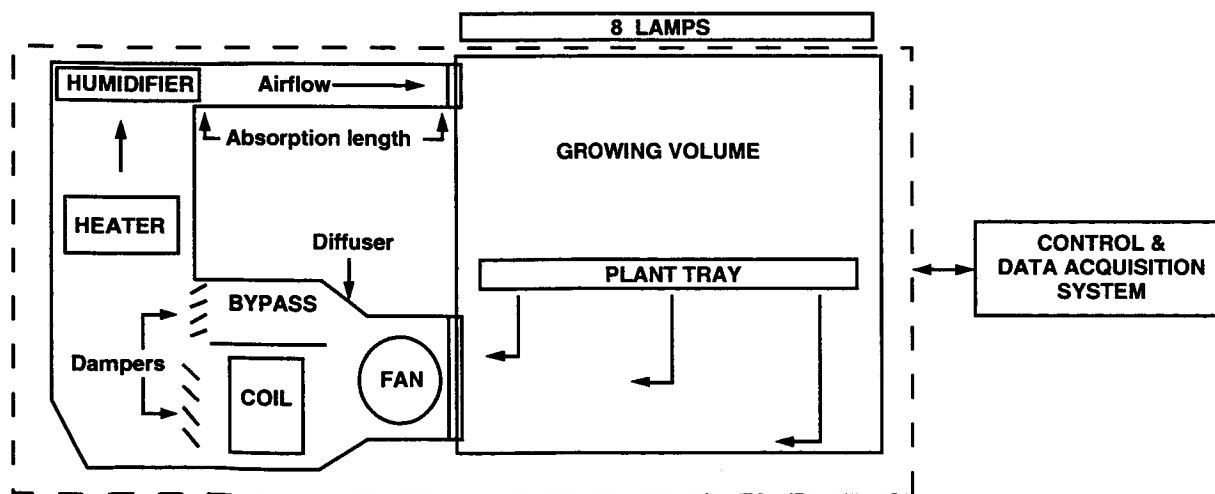

Figure 3. Engineering development unit block diagram.

To develop a better understanding of the the temperature and relative humidity control requirements, see figure 4. The slashed portion of the graph highlights the minimum air temperature attainable due to the minimum water temperature delivered by the water chiller, which cools the water entering the cooling coil. The shaded portion of the graph shows the temperatures and relative humidities not achievable due to the characteristics of the cooling coil. What makes achieving the required range so challenging is the use of off-the-shelf components which are designed to control temperature and relative humidity over very small ranges and with low accuracies. For example, temperature control required for a building's air-conditioning system is typically 20-26 °C with no set control accuracy, except to note that the system should reheat when the temperature drops below 20 °C. And relative humidity control for a building is normally 50% ±10% RH (ref. 5). Therefore, trying to use off-the-shelf components to attain ranges and accuracies for which they were never designed is difficult. Also, temperature and relative humidity are dependent upon each other. For example, a change in air temperature with a given specific humidity will cause a change in relative humidity as shown on a psychrometric chart (ref. 4). These realities become even more challenging when controlling temperature and relative humidity in a closed environment.
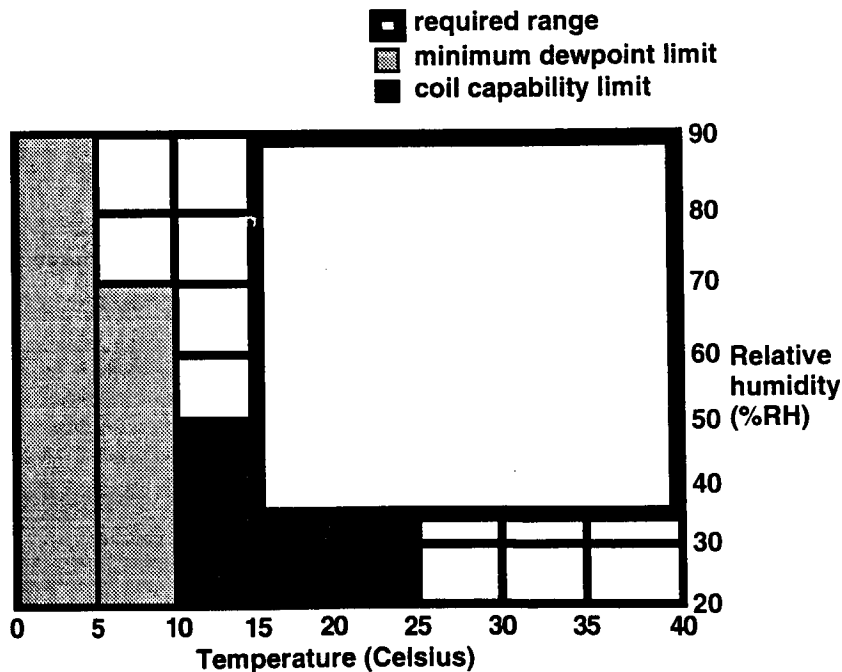

Figure 4. Envelope for control of temperature and relative humidity.

The five goals of the EDU are listed below.

1. Perform hardware performance evaluations of the air-conditioning (AC) components to ensure that they are sized properly and function according to the manufacturers' specifications. The AC components include the fan, the coil, the actuators which control the dampers, the heater, the humidifier, the water chiller, and the mixing valve which controls the water temperature entering the coil.

2. Evaluate the operation and placement of sensors to provide for accurate and reliable feed-back information.

3. Evaluate the computer system, both the software and input/output hardware, to determine suitability for the final CGRC.

4. Develop a working control scheme for temperature and relative humidity control over the required range shown in figure 4.

5. Perform tests to determine if and how the AC system volume can be reduced.

The results obtained from the testing of the EDU are summarized in the following text.

1. Hardware performance evaluation

Most of the hardware performed as expected and according to the manufacturer's specifications. The components that differed from the manufacturer's specifications and from the project's expectations are detailed below.

The variable speed fan is required to control the air velocity inside the chamber from 0.3 to 1.0 m s^{-1} ± 10%, as measured from the top plane of the plant canopy. The fan was able to perform these requirements and can actually produce air speeds lower than 0.3 m s^{-1}, however, the lowest air velocity measurable with the flow sensors is 0.3 m s^{-1}.

The dampers, controlled by linear actuators, manipulate the amount of airflow through the coil and through the bypass to control temperature. The range of airflows available through the coil vs. damper positions were tested and determined if linear. The airflow with respect to damper position is linear only when the actuators are working in the 10% to 50% range. Tables reflecting this data were stored in the computer and are used to generate the proper actuator command to produce the required airflow necessary for temperature control.

The heater does not have the capacity to reach the high temperature points for which it was intended because the energy input to the EDU is much smaller than anticipated. Specifically, the heat input from the lamps is only 1 kwatt as compared to the 6 kwatts expected. The heater had to compensate for both the heat that the lamps were expected to provide and the heat lost due to leaks in order to test the control algorithm for the final CGRC, which is expected to have 6 kwatts of energy input from the lamps. Therefore, the heater had insufficient capacity to reach the high temperatures. Since it is expected that the CGRC will have 6 kwatts of energy input from the lamps due to closure, the heater's capacity will be sufficient to reach the high temperature points.

2. Sensor evaluation

Temperature, humidity, air velocity, and photosynthetic photon flux (PPF) are measured using a variety of sensors. Only problems associated with temperature and humidity measurements were experienced. The thermocouples initially used for temperature feedback, accurate to 1 °C, were replaced with resistance temperature detectors (RTD's), accurate to 0.2 °C. This allowed for much

tighter control. Also, the RTD's located inside the chamber are shielded and aspirated to negate any effects from the overhead lamps. Chilled mirror sensors are the most accurate for measuring the dew point to obtain relative humidity. However, since the air swirls within the chamber, even under the plant tray, the readings from the chilled mirror were unstable and could not be used for control. Therefore, Vaisala® temperature (measured with an RTD) and relative humidity sensors are used to provide feedback from the chamber and at set locations in the ducting. The Vaisala® sensors, calibrated at the factory with a chilled mirror sensor, are very stable and accurate. They are sturdy, easily mounted and easily integrated with the computer system. The Vaisala sensor located inside the chamber is also shielded and aspirated to negate any effects from the overhead lamps.

3. Control system software and hardware evaluation

A process control system software package was used on an IBM PC compatible and worked well for this application. It was simple to develop and experiment with various control algorithms because of its intuitive graphical format. The input/output hardware which processed feedback information from the sensors and sent it to the computer via one twisted, shielded cable also worked very well. Both the software package and the input/output hardware will be used on the CGRC.

4. Control scheme development for temperature and relative humidity control

The first control scheme tested was a complex control algorithm developed from a mathematical model of the EDU on Matrix$_x$®, a controls modeling and simulation software package. In testing this control scheme it was noted that actual control could be accomplished with a more simple, straightforward control scheme. The simple control scheme actually controlled temperature and relative humidity better than the complex algorithm and was easier to manipulate. This control scheme, shown in figure 5, consists of two proportional, integral, derivative (PID) loops. One PID controls the damper positions for temperature control and the other PID sets the mixing valve position for humidity control. For humidity control, a nested loop was necessary to effectively control the temperature of the water entering the coil, therefore feedback of the temperature of the water entering the coil was fed to another PID. In conclusion, the AC design, control hardware, and control software proved successful in meeting the goals of the CGRC Requirements Specification for control of temperature and relative humidity (ref. 3).

Control was established for over 90% of the required range shown in figure 4 to within 1 °C and 3% RH. Some high humidity, high temperature points on the envelope in the upper right hand corner of the graph are not obtainable due to the leak rate of the EDU. The heater and the humidifier cannot keep up with the leak rate at the high levels. It is expected that these points will be achieved in the CGRC due to closure. Some low humidities and low temperatures on the bottom, left portion of the graph cannot be achieved due to the chiller and coil characteristics. The chiller must cool water travelling through the coil to a minimum of 8 °C in order reach these points. The 120 foot long pipeline from the chiller to the coil is insulated to minimize heat gains, however, the water entering the coil is 10 °C at its coldest. Therefore, some of the lower temperatures and relative humidities cannot be reached and will not be achieved in the CGRC. Some high humidity points, located along the 90% relative humidity line, could not be reached in the EDU. These points could not be reached due to the leak rate, the lack of plant transpiration (because plants were not grown in the EDU), and the lower

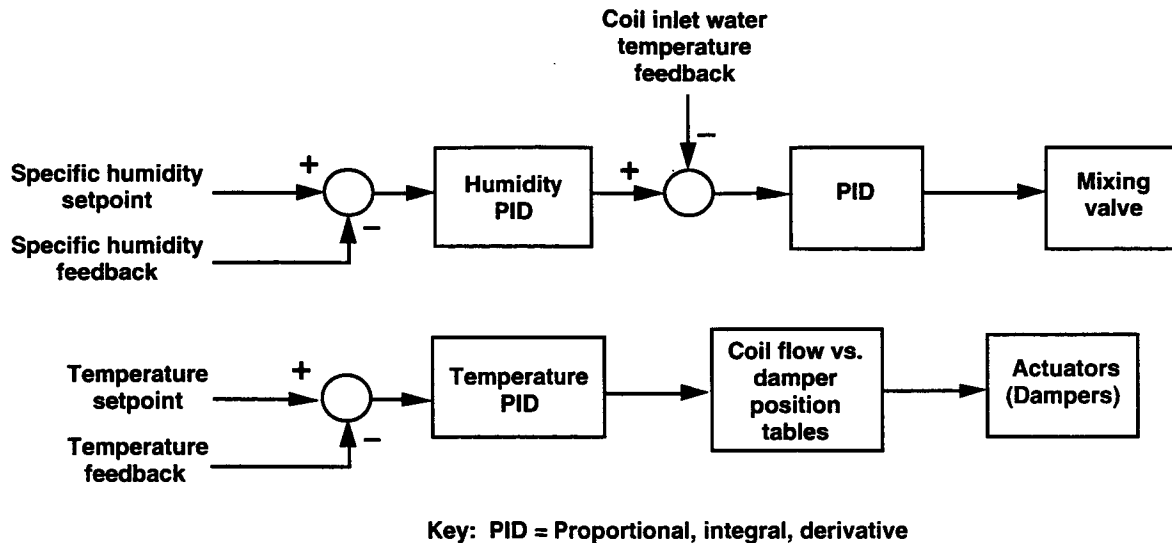**Key: PID = Proportional, integral, derivative**

Figure 5. The EDU control scheme block diagram.

level of heat input from the lamps than expected. It is anticipated that these points will be achieved in the CGRC due to closure.

5. AC volume reduction

The two main drivers behind the volume of the AC system are the coil size and humidifier absorption length. The coil area is large to prevent air from traveling too fast across the coil such that condensed water flies off into the ducting. The scientists require that no water flies off the coil because gases that are being measured can dissolve in that water. The humidifier absorption length was determined from the manufacturer's recommendation to allow for complete absorption of the steam into the air before it enters the chamber. Steam is not allowed to enter the chamber due to plant stress and to eliminate water droplets in which gases could dissolve. Tests were conducted to determine if the coil area could be reduced and if the humidifier absorption length could be shortened, while maintaining the same level of control.

Tests concluded that reduction in the area of the coil can possibly be achieved by increasing its length, thus maintaining the total energy removal capacity of the coil. Decreasing the area of the coil will decrease the diffuser outlet area and the diffuser length, therefore decreasing the AC system volume. Further analysis will determine exactly how much the coil face area can be reduced. Identifying the location of the actual absorption of the steam along the duct proved that the humidifier absorption length may also be reduced without allowing steam to enter the chamber.

FUTURE WORK

Results from the testing of the EDU are currently being applied to the final designs of the air-conditioning system. Detailed designs of the chamber are almost complete and preliminary designs of the hydroponic, pressure control and gas control systems are underway. Testing of the pressure

control system and the oxygen removal system, part of the gas control system, will occur over the next few months. Also, a model of the EDU which was created to develop control schemes for temperature and relative humidity control is being expanded to include the other systems in the CGRC.

CONCLUSION

Since the CGRC is the first of its kind, it was necessary to build an EDU in order to gain experience in designs never before tried. Testing of the EDU allowed design engineers to gain experience with the air-conditioning hardware and sensors, and enabled the development of a working control scheme for temperature and relative humidity control. It also provided added confidence in the possibility of shrinking the size of the cooling coil and reducing the humidifier absorption length. All of this knowledge gained will make the CGRC a better research tool for the study of plant growth in a closed environment.

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BIOGRAPHY

Kimberly Wagenbach received her Bachelors of Science in Electrical Engineering (BSEE) in 1983 and her Masters in Business Administration (MBA) in 1988 from the University of Santa Clara. She began her work at NASA Ames Research Center in 1983 on the Frog Embryology Experiment, a life sciences experiment which will fly aboard the Shuttle's spacelab. Ms. Wagenbach has worked on a variety of life sciences experiments, control systems to support aircraft, and more recently, has worked on projects in the advanced life support arena. Currently, she is the Engineering Project Manager for the Crop Growth Research Chamber Project. Also, Ms. Wagenbach is a member of the Ames Speaker's Bureau and an Ames college recruiter.