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CONCEPTUAL DESIGN OF A CLOSED LOOP NUTRIENT SOLUTION DELIVERY SYSTEM FOR CELSS IMPLEMENTATION IN A MICRO-GRAVITY ENVIRONMENT

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ABSTRACT This paper describes the results of a study to develop a conceptual design for an experimental, closed-loop fluid handling system capable of monitoring, controlling, and supplying nutrient solution to higher plants. The Plant Feeder Experiment (PFX) is designed to be flight tested in a micro-gravity (micro-g) environment and was developed under NASA's In-Space Technology Experiments Program (INSTEP). When flown, PFX will provide information on both the generic problems of micro-g fluid handling and the specific problems associated with the delivery of nutrient solution in a micro-g environment. The experimental hardware is designed to fit into two middeck lockers on the Space Shuttle, and incorporates several components that have previously been flight tested.

AMONG THE PROBLEMS encountered in designing devices to function under the micro-gravity (micro-g) conditions of spaceflight, some of the most common involve the handling of fluids. The general fluid handling problem encompasses monitoring and control of fluid composition, mixing of fluids, and fluid transfer. The problem becomes critical in the design and operation of life support systems because of the importance of water and aqueous solutions in such systems. This is especially true in the development of Controlled Ecological Life Support Systems (CELSS) with hydroponic systems for higher plants.

The objective of the study was to develop a conceptual design for an experimental fluid handling system which would be tested in flight under micro-gravity conditions. The Plant Feeder Experiment (PFX) will provide an evaluation of fluid handling capabilities, and supply data on both generic and CELSS-specific fluid handling problems. The specific goals the experiment was designed to address included: 1) measurement of solution monitoring capabilities under micro-g conditions; 2) measurement of solution control capabilities under micro-g conditions; 3) measurement of the capability to condense, collect and recycle water vapor; and 4) measurement of the capability of different nutrient solution delivery/recovery system designs to provide water and nutrient elements to higher plants under micro-g conditions.

PREVIOUS AND ON-GOING WORK

Much of the prior work in the area of micro-gravity nutrient delivery systems has been done by Soviet investigators. In general, they have focused their efforts on solid substrate systems, using either direct soil analogs or fibrous materials such as rock wool [1,2]. Functional operation of these systems has generally been limited to simply adding water or nutrient solution to the rooting substrate, thus avoiding most of the problems associated with the handling of fluids in the micro-g environment. To date, their results with living plants have been very inconsistent; e.g., some species have grown well while others died or grew poorly during flight.

They have theorized that this inconsistency is due to a lack of control over the plant environment including the nutrient supply to the roots.

The European Space Agency (ESA) has also designed and conducted ground testing of several plant growth systems for space flight. These systems have been developed for use both on the Space Shuttle and on the European Recoverable Carrier (EURECA). The ESA designs have stressed the use of soil analogs [3], also avoiding many of the problems associated with fluid handling in the micro-g environment.

Under NASA sponsorship, several U.S. scientists have developed nutrient delivery system designs for micro-g use. One of the first papers on this topic described the use of a sheet of semipermeable membrane as a barrier between nutrient solution and plant roots [4]. This membrane barrier served as a means for maintaining separation of the liquid and gas phases in the root environment, thereby providing a partial solution to one of the micro-g fluid handling problems. This membrane design was modified by a team of scientists working at Kennedy Space Center (KSC), and converted into a tube-within-a-tube arrangement. This modified design has been ground tested [5] at KSC, along with Purdue University and Ames Research Center (ARC). The results of this test program have generally indicated that the design supports adequate plant growth, but that growth is slower than that measured in hydroponic systems of conventional 1-g design.

Two of the NASA-sponsored Centers for the Commercial Development of Space (CCDS), Bioserve Space Technologies at the University of Colorado (Bioserve) and Wisconsin Center for Space Automation and Robotics at the University of Wisconsin (WCSAR), are currently conducting design studies in the area. The work at Bioserve is of a generic nature and has included several studies addressing micro-g plant growth systems in conjunction with ARC. These studies have included evaluation of porous plastic tubes for nutrient solution supply. To date, Bioserve has not published any detailed designs for these systems, but they have discussed their designs at several NASA-sponsored meetings. WCSAR has focused on a hybrid system design which supplies nutient solution to a solid clay-like substrate by gradually leaking it from a porous, sintered stainless steel tube embedded in the substrate [6]. The WCSAR system is currently undergoing ground tests at the University of Wisconsin.

DESIGN OF EXPERIMENTAL HARDWARE

The initial overall design configuration of the PFX hardware is pictured in Figure 1. The design consists of five subsystems; the reservoir, sensing manifold, control manifold, nutrient solution delivery/recovery subsystem, and the water vapor condensation and recovery system [7]. The development of each subsystem design is discussed in the following sections.

RESERVOIR SUBSYSTEM

Table 1 summarizes the principle methods we identified for organizing the reservoir subsystem. Two categories of subsystem design were developed initially: single reservoir and dual reservoir.

Table 1. Reservoir Configuration Design Options

1. Single Reservoir
   a. Stationary
   b. Rotating
   c. Divided, Stationary
2. Dual Reservoir
   a. Large/Small Volumes
   b. Identical Volumes

Three options were identified for single reservoir systems, two using an open tank (Figure 2 a,b) and one using a divided tank (Figure 2 c) . Two of the single tank options (Figure 2 a,c) require mechanical pumps to transfer the solution. Because of the problems associated with pump priming under micro-g conditions, these design options were identified as the least desirable. One of the open tank options was a centrifugally-powered reservoir in which the tank was rotated about its main axis (Figure 2 c), and a pitot tube pickup was immersed in the liquid film coating the wall of the rotating drum. This design option has several desirable features with regard to mixing, monitoring and control of the solution composition, but requires more volume, has a higher power use, and produces more vibration than the other options.

The two design options we identified as most desirable were the dual reservoir options. One option (Figure 2 d) utilizes a bladdered tank and a small bladdered accumulator (to receive the solution flowing out of the nutrient delivery/recovery system), while the other uses two bladdered tanks of the same volume (Figure 2 e). Another option considered for the accumulator was a piston driven,

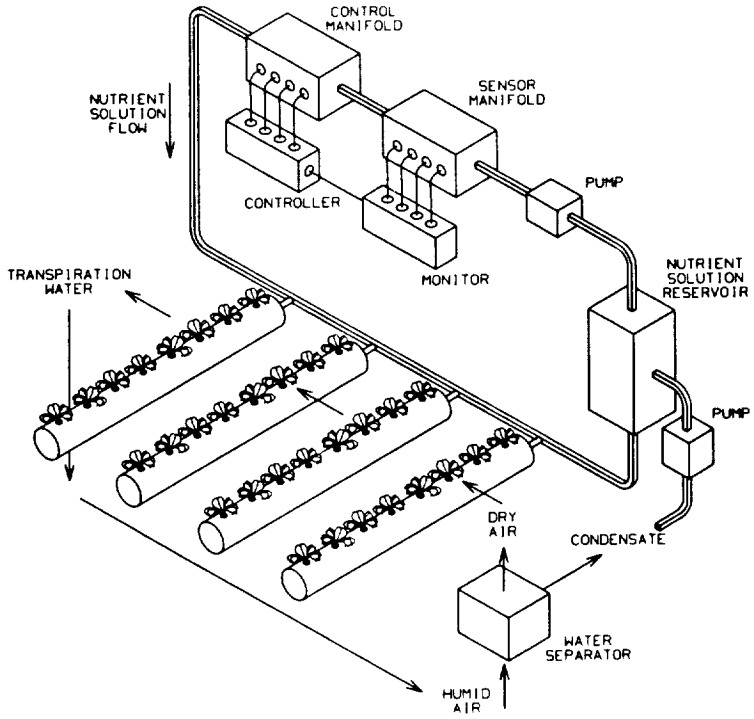

FIGURE 1. Initial PFX Hardware Configuration

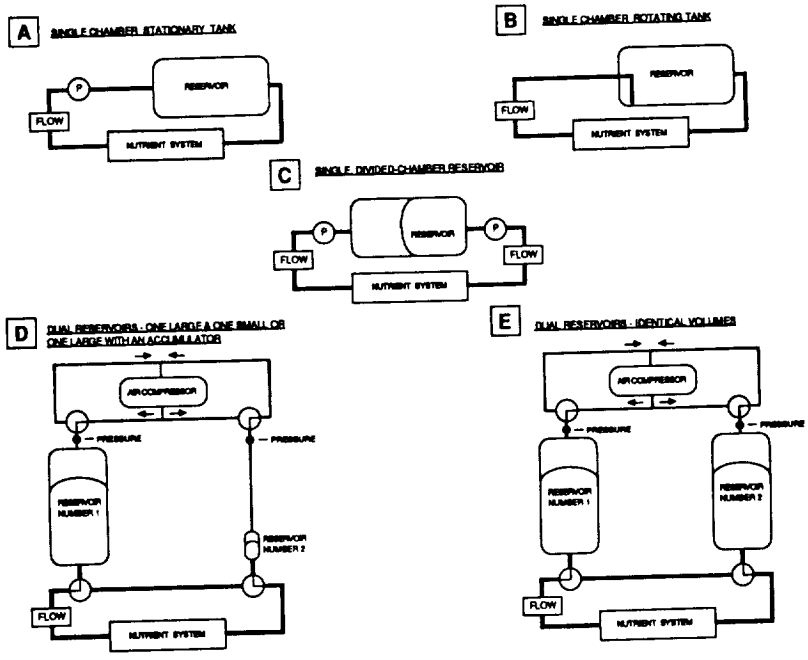

FIGURE 2. Reservoir design options.

syringe-like system. The piston option was eliminated because of the potential problems of sealing around the piston.

In order to support the testing of solution mixing capabilities, we selected the option illustrated in Figure 2 e as the baseline for the experiment design. This option requires an compressor which pumps air from one bladdered tank to the other, thus creating fluid flow through the system. The tanks used in both options are flight-tested hardware derived from Lockheed's Research Animal Holding Facility (RAHF). This design option also provides the capability for precise control of the liquid pressure differential across the nutrient delivery/recovery system under test by control of the reservoir air pressures.

SENSOR MANIFOLD

Monitoring solution composition is complicated by several factors, most notably the lack of liquid/gas phase separation. Phase separation problems as simple as an air bubble adhering to the active portion of a sensor can produce erroneous composition readings. The sensors themselves must be robust enough to withstand launch, with an operating stability that does not require recalibration during flight.

Table 2 lists the kinds of solution measurements required and the types of sensors considered for each. Ultimately, we determined that ion-specific electrodes provided the most rugged, stable devices for monitoring solution ion concentrations. Gas-specific electrodes were chosen to monitor the concentrations of oxygen and carbon dioxide dissolved in the solution. A platinum RTD was chosen for solution temperature monitoring and standard pH and electrical conductivity electrodes chosen for measuring these bulk solution parameters.

The initial design for this manifold is illustrated in Figure 3. A static mixer has been included in the design to assure complete mixing of the solution flowing through the bore of the manifold. By properly positioning the mixer, a homogenous liquid stream is supplied to the sensors, while simultaneously preventing the clogging of sensing elements by air bubbles.

CONTROL MANIFOLD

The control functions incorporated into this design included specific elemental concentrations, temperature, pH, electrical conductivity and dissolved oxygen and carbon dioxide concentrations. The control methods we evaluated for use in this experiment are listed in Table 3.

Table 2. Sensor Manifold Design Options

1. pH Measurement
   a. Electrochemical
   b. Fiber Optic
2. Electrical Conductivity
   a. Conductivity Electrode
3. Ion Concentration Measurement
   a. Ion Specific Electrodes
   b. Ion Chromatograph
   c. Optical Absorbance
4. Temperature
   a. Thermocouple
   b. Thermistor
   c. RTD
   d. Integrated Circuit
5. Dissolved Gas Concentration
   a. Semipermeable Membrane Sensor
   b. Headspace Gas Sampling

Table 3. Control Manifold Design Options

1. pH Control
   a. Electrochemical
   b. Chemical
2. Electrical Conductivity Control
   a. Direct Solution Addition
   b. Trans-membrane Solution Addition
3. Ion Concentration Control
   a. Passive Control by Ion Exchangers
   b. Direct Chemical Addition
   c. Electrochemical Addition
4. Temperature Control
   a. Thermoelectric Unit
   b. Chilled Water/Electric Heater
5. Dissolved Gas Concentration Control
   a. Direct Gas Injection/Chemical Absorption
   b. Trans-Membrane Addition/ Removal

The design of the control manifold body is very similar to that of the sensor manifold. Miniature metering pumps are incorporated into the design to add distilled water or concentrated nutrient solution for electrical conductivity and elemental concentration

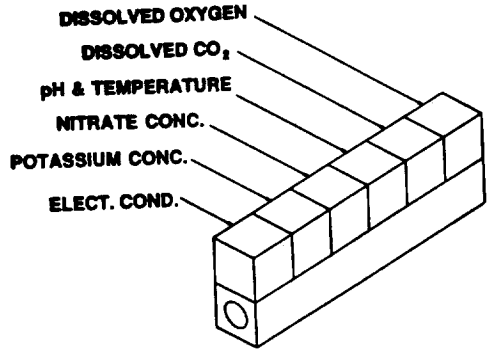

FIGURE 3. Sensor manifold design.

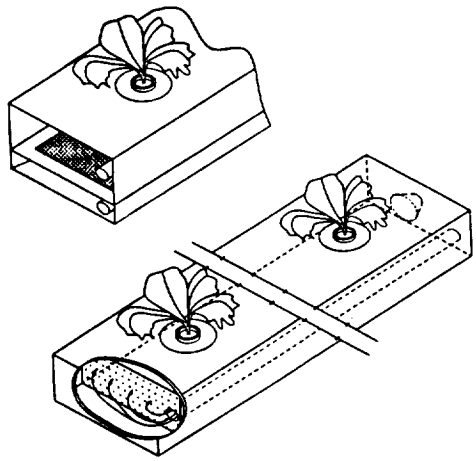

FIGURE 6. Solution culture design.

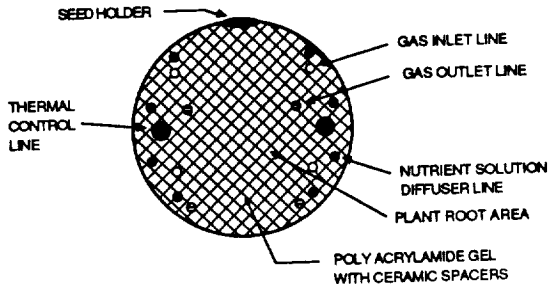

FIGURE 4. Polyacrylamide gel system design.

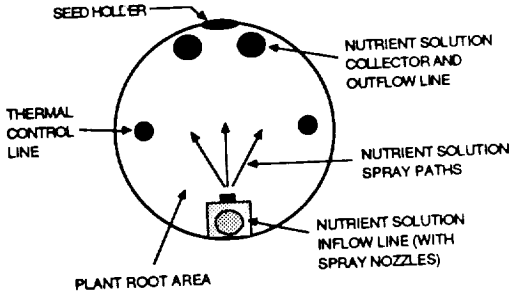

FIGURE 7. Aeroponic design.

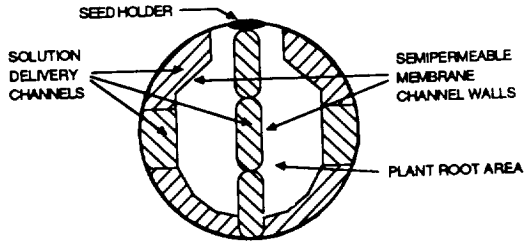

FIGURE 5. Semipermeable membrane design.

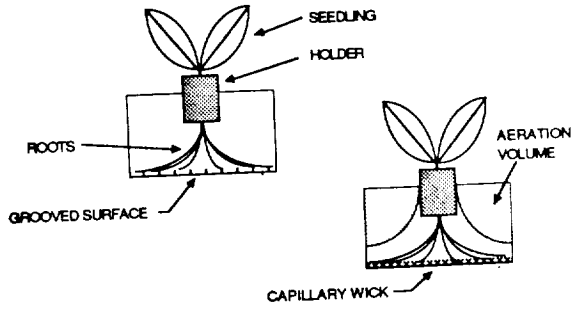

FIGURE 8. Heat pipe designs.

control, and acid or base to control solution pH. Temperature is controlled with an electrical heater bucked against a coolant jacket supplied with cool water from the Space Shuttle. Dissolved gas concentrations (O_2 and CO_2) are controlled by a semipermeable membrane equipped gas/fluid exchangers.

NUTRIENT DELIVERY/RECOVERY SUBSYSTEM

Table 4 lists the different families of nutrient solution delivery/recovery system identified for potential testing in this experiment. Because one of the main objectives of the experiment is to qualitatively determine the functional characteristics of these systems, we plan to support at least four different systems in the design.

Table 4. Nutrient Delivery/Recovery Design Options

1. Solid Substrate
   a. Soil
   b. Soil Substrate
   c. Ion Exchange Resin
   d. Gel
2. Nutrient Film Technique
3. Solution Culture
4. Aeroponics
5. Hybrid Design
6. New Design
   a. Tubular Membrane (e.g., KSC)
   b. Plastic, Ceramic or Metal Wick (e.g., WCSAR)
   c. Heat Pipe Technology

Figures 4 through 8 illustrate several of the design concepts we feel to be the most promising. Determination of which of these systems will be flight tested will be based on ground evaluations and supporting flight tests (e.g., KC-135).

WATER VAPOR CONDENSATION AND RECOVERY SUBSYSTEM

The efficient condensation and effective collection of water vapor is a particularly difficult problem in the micro-g environment. In any CELSS system with higher plants, however, there will be a strong need to maximize this capability. Table 5 lists the technology options identified for this subsystem. Because it has already been extensively flight tested, we decided to use the Lockheed RAHF condensate collection system in this design.

Table 5. Water Vapor Condensate/ Recovery Design Options

1. Hydrophillic/Hydrophobic Separator (e.g., RAHF)
2. Vortex Water Separator
3. Condensing Heat Exchanger with Wick
4. New Design

SYSTEM CONCEPTUAL DESIGN

The detailed conceptual design for the PFX hardware is illustrated in Figures 9 and 10. The current design is baselined to fit into two Shuttle middeck lockers. The main locker houses the reservoirs, monitoring and control manifolds, most of the fluid control components, and the experiment control computer and associated interface electronics (Figure 9). The second locker contains the nutrient delivery/recovery systems to be tested, the water vapor condensate/recovery system, and the remaining fluid control components (Figure 10).

We have also developed a design which integrates and slightly reconfigures the hardware for packaging in a Shuttle double middeck locker. The use of a double locker has several advantages, most notably the reduction in the number of connecting lines (both fluid and electrical) exposed to the middeck environment. The primary drawback is simply the scarcity of double middeck lockers in which the experiment could be packaged.

SUMMARY AND CONCLUSIONS

The flight experiment hardware described here has been developed to support an engineering assessment of several critical functions of micro-gravity fluid handling. The functions we intend to assess include several that are generic to micro-gravity fluid handling as well as some that are specific to the handling of fluids for a CELSS design. To help keep hardware development costs down, the design incorporates existing flight-tested components wherever possible. The PFX hardware design we have developed can be accommodated on the Shuttle middeck, packaged either in two single lockers or in one double locker.

ACKNOWLEDGEMENT

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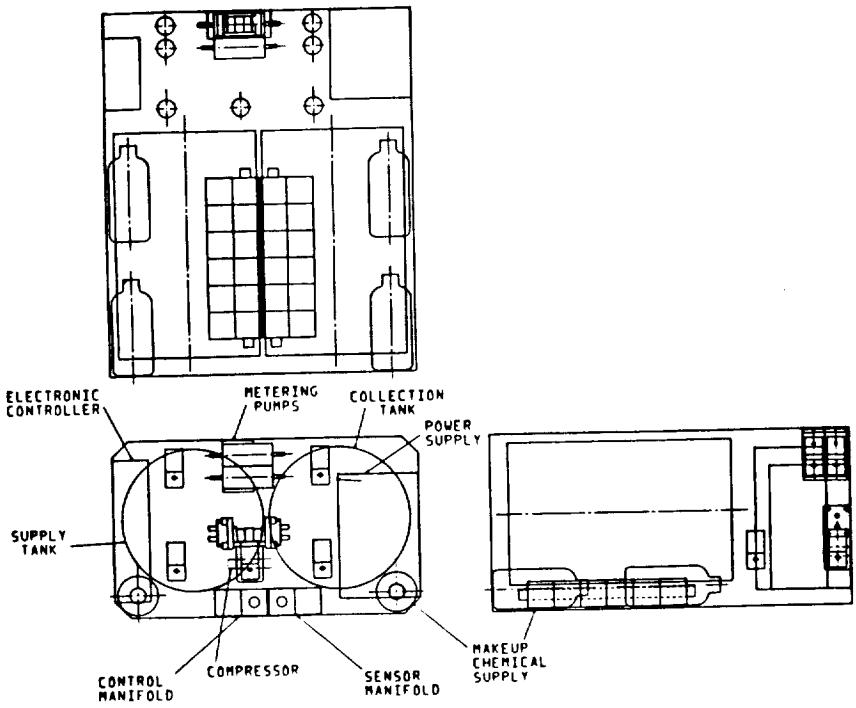

FIGURE 9. Three view layout drawing of main locker.

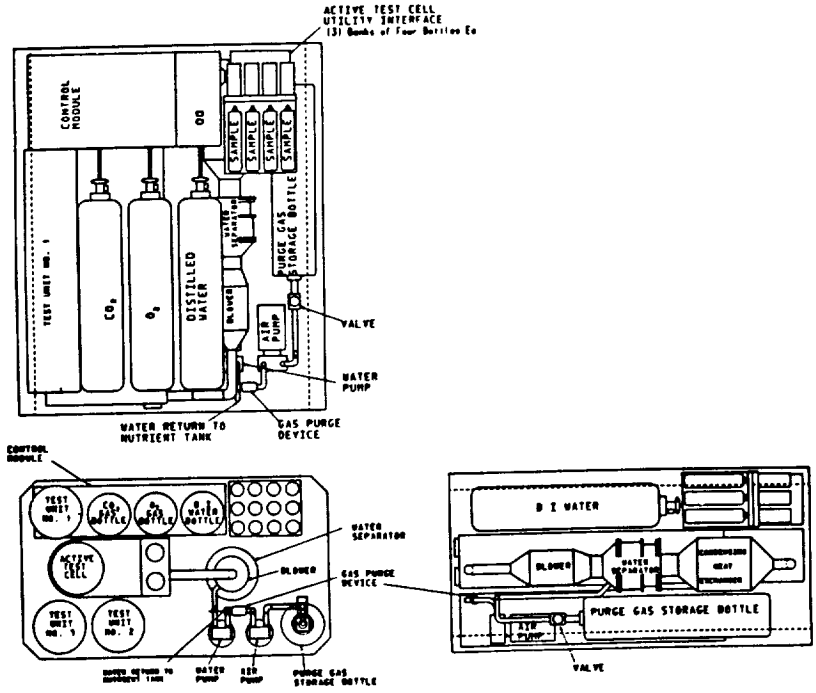

FIGURE 10. Three view layout drawing of second locker.

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