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DESIGN OF BIOMASS MANAGEMENT SYSTEMS AND COMPONENTS FOR CLOSED LOOP LIFE SUPPORT SYSTEMS

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The goal of the EGM 4000/1 Design class was to investigate a Biomass Management System (BMS) and design, fabricate, and test components for biomass management in a closed-loop life support system (CLLSS). The designs explored were to contribute to the development of NASA's Controlled Ecological Life Support System (CELSS) at Kennedy Space Center. Designs included a sectored plant growth unit, a container and transfer mechanism, and an air curtain system for fugitive particle control. This report summarizes the work performed by the class members.

SECTORED PLANT GROWTH UNIT (SPGU)

The goal of the Plant Growth group was to engineer the development of a plant growth unit in which planting, harvesting, and refurbishing would take place. The system that was designed, a Sectored Plant Growth Unit (SPGU), models a sector of the aeroponic plant growth unit conceptually designed for a Controlled Ecological Life Support System (CELSS), by the EGM 4000 Advanced Missions Space Design class, during the fall of 1990.

This unit, shown in Figs. 1 and 2, provides a growth promoting environment for all stages of crop development. Seed holders provide support as the individual plants grow. The roots receive a nutrient solution in the form of a mist (Fig. 3). The nutrient mist, along with separated plant particles (leaves, root pieces, etc.), are removed by the application of pressure and velocity gradients.

The SPGU is cleaned by a hydro-refurbishing system (Fig. 4) that cuts the plant at the root line, discharges all material in the seed holders, and liberates the edible and inedible parts of the plant from the unit. After the crop is harvested, the inedible biomass is removed from the SPGU with high-discharge water and air jets.

Fig. 1. Sectored plant growth unit (top view).

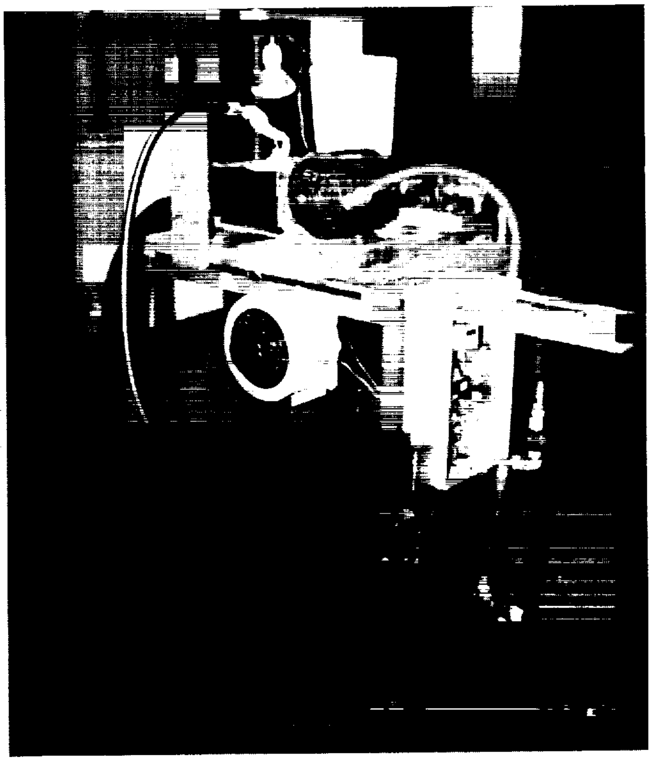

Fig. 2. SPGU and support systems.

As the CELSS research continues on the ceramic growth medium, several complications have arisen such as pore clogging. It was a goal of the Plant Growth group to avoid the problems that the porous tube and tray projects at Kennedy Space Center have encountered, while not overlooking other problems inherent to an aeroponic and hydro-refurbishing system, such as clogging of the misting and refurbishing nozzles.

During the conceptual design phase of the project (growing plants in a microgravity environment) the Plant Growth group took into account the planting, harvesting, and refurbishing activities, and how they apply in an integrated system. In the fall of 1990, the group determined some of the necessary criteria for a plant growth unit (PGU) and suggested a possible design.

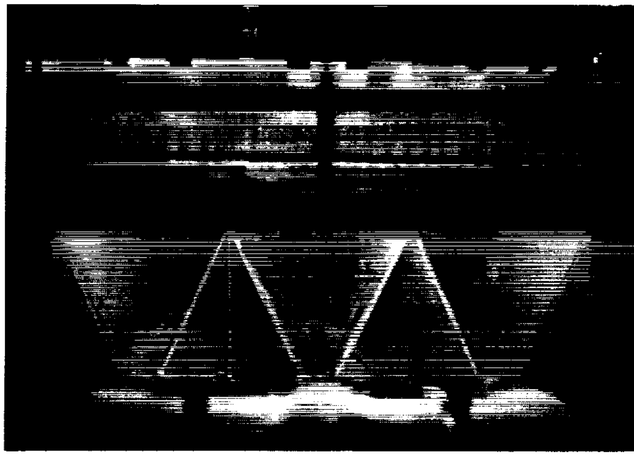

Fig. 3. Activated SPGU (side view).

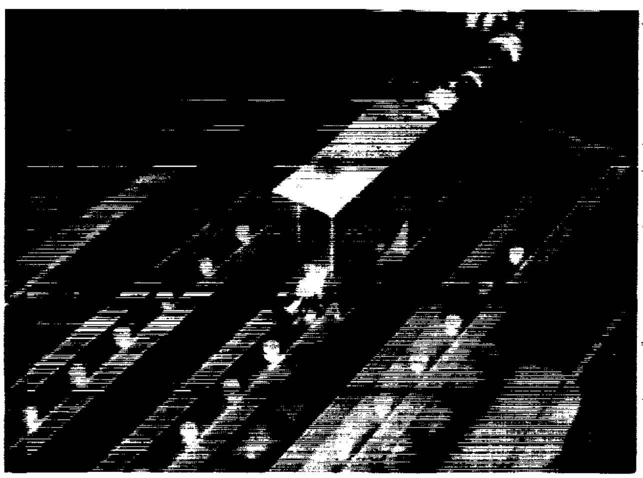

Fig. 4. Hydro-refurbishing block on SPGU surface.

In the spring of 1991, the design was revised, a prototype was built, and the concept was tested in an SPGU. Radishes were chosen as the SPGU crop because of their relatively small size and rapid growth rate.

Several methods are already in use for planting crops in nonsoil media, so little time was spent in designing a planting system for the SPGU. Likewise, harvesting, as an individual activity, received very little focus. By the design of the SPGU, harvesting is basically a continuation of the refurbishing process.

Although aeroponics is a proven method of plant nutrition, very little research has been performed using a vacuum system and pressure gradients to control the aeroponic mist flow. There are distinct differences between the SPGU and the Vacuum Oriented Nutrient System (VONS), currently being explored by Bill Cox at Kennedy Space Center. The SPGU is one unit containing many plants, rather than many units containing one plant each, which is typical of VONS. In a microgravity environment, the vacuum may become important, providing a way to keep the mist in the nutrient delivery system. Also, little research has been performed on the use and effectiveness of water jets (knives) to clean organic and inorganic materials out of a plant growth chamber. Thus, considering the time constraints for the project design, the focus of the Plant Growth group was directed towards the unexplored aspects of a vacuum-oriented, aeroponic plant growth unit employing a hydro-refurbishing system. The Segmented Plant Growth Unit relates directly to the PGU conceptually designed for use in CELSS. The PGU is a complete system of stem and root chambers that are separated by coaxial cylindrical surfaces. These surfaces have fixed and moving nozzles that provide an aeroponic mist for plant nutrients, and precise, high-pressure sprays for refurbishing. By research and development, the final design of the SPGU should be large enough so that the data can be extrapolated to a full-size of PGU.

The placement of a seed prior to germination, and the orientation with which the plant grows after seed germination, are vital elements of a plant's growth and development. Many factors such as light, air, water, pressures, and forces, will affect how the plant develops. Because the design group intended to focus primarily on the relatively unexplored aspects of the system (the hydro-refurbishing and vacuum oriented aeroponic systems), no planting schemes were thoroughly investigated. However, several ideas were envisioned. Peat pellets, inflatable balloons, polymer funnels, and especially designed pieces of filter paper or perforated plastic were all ideas that may be used to hold seeds in specific orientations. With more research and testing, any of these ideas may be feasible for integration into a full-scale PGU.

The nutrient delivery system developed for the SPGU possesses the best aspects of aeroponics and VONS. The system allows the growth of many plants in one chamber, supplies the roots with nutrients by a misting action, and employs a vacuum for nutrient solution recovery. The system was developed for use in microgravity by designing the actual plant growth unit with certain specifications. For example, nutrient solution was not to escape from the root chamber, except through the vacuum, regardless of its orientation when being tested on Earth.

Cleaning the PGU is a serious problem. Currently, it takes a group of six people a week to clean out the area required to feed one astronaut. Thus, a major design requirement would be to drastically reduce cleaning time. It was proposed to use water jets to clean the entire PGU within a matter of minutes. These water jets would be required to run at a high pressure in order to concentrate a large force over the desired area. Attempting to keep the hydro-refurbishing system small, the volume flow rate was specified to be under 1 gpm. The water knife would be used to cut off the top portion of the plant while another jet would free the root mass and remaining stem from the PGU. Ultimately, a sensor-based, intelligent system would carry and selectively aim the nozzles.

The opposing gravity test was performed to observe the delivery and recovery of the nutrient solution in an opposing gravity field. This test was performed to confirm that the SPGU would work in a microgravity situation. The SPGU was oriented such that the nutrient solution entered from a lower potential energy state, with respect to gravity, than it was recovered from.

In other words, it was rotated such that the nutrient spray entered from the bottom, and the vacuum pulled it out of the top. In this orientation, the solution accumulated until an equilibrium water depth of about 1.5 inches was obtained. In this case, the vacuum was run at about 70% of the vacuum's maximum motor speed. As the vacuum's power was increased to 100%, the equilibrium water height decreased to approximately 0.5 in. In addition to increasing the vacuum power, supplying the nutrient recovery vacuum with more air helped decrease the equilibrium water level in the SPGU. By adding more holes between the top surface and the root chamber (in addition to the seed holder ports), more air was supplied to the vacuum. When this was done, the equilibrium water level in the SPGU completely disappeared; thus, the spray went straight from the misting nozzles to the recovery vacuum. Ideally, this would allow the roots to remain moist without being completely saturated. The tests performed on the SPGU, with respect to nutrient delivery in microgravity, showed that a vacuum-oriented nutrient solution recovery system could offer an alternative to current systems. Because the tests were performed under opposing gravity, it is conceivable that in microgravity, parameters such as vacuum pressures and flow rates could be reduced. Potential problems with separation of nutrient solution and vacuum fluid are foreseen.

A prototype SPGU surface was developed to perform refurbishing tests. The prototype surface has three rows of seed holder ports, with eleven ports in each row. Refurbishing tracks were milled exactly as in the actual SPGU. The main purpose of this refurbishing plate was to place mature radishes (or other small crops) into the port, and cut them with the refurbishing nozzles. It would not be necessary to wait for the plants to germinate and mature in this case. Because of the inability to find mature radishes with stems still attached, cutting tests were performed with celery. Celery has a very high percentage of cellulose, and is one of the strongest vegetable crops. Thus, it was hypothesized to be an optimal test for the refurbishing nozzles. At a water pressure of 500 psi, the fan nozzle was able to cut six celery pieces (1/4 in diameter each) in approximately 5 s. With increased pressures and a more efficient nozzle system, the refurbishing time may possibly be further reduced.

CONTAINER AND RECEIVING MECHANISM (CARM)

The Container and Receiving Mechanism (CARM) is a device designed to transport and store solid matter. In a microgravity environment, containment is a problem because of the tendency of particulate matter to disperse randomly about the crew compartment.

A canister system does not currently exist in CLLSS. Any research and development will prove highly beneficial to the BMS. Last semester two approaches were examined to develop a transport system. CARM could incorporate with either the pneumatic or magnetic belt ideas. In a CLLSS there is a need for the containment and storage of the edible biomass produced. The absence of a gravitational force necessitates the containment of all particles. In microgravity loose particles pose a unique problem since they disperse throughout the surrounding compartment. As a solution, a CARM that is multifunctional has been proposed: its primary function is the sealed transport and transfer of food to a processing unit; the secondary function is the storage of food until further processing. CARM's use should not be limited to the transfer of edible biomass between the Plant Growth Unit and Food Management. It has numerous applications in the movement of mass between all compartments in a CLLSS.

Several different transfer systems were evaluated before final selection of the CARM. These included an L-channel device, a plunger system, and a roller method. After examining the different options, a final selection for a transfer mechanism was made. The CARM system chosen consists of a hard shell cylinder, a bag, and an interlocking mechanism (Fig. 5).

A cylindrical shape has several advantages: ease of transport, cleaning, and storage. This shape also adapts itself to the transport mechanism presented last semester in EGM 4000. For testing purposes a clear cylinder was chosen so that the internal environment could be observed. The hard shell construction allows air pressure to be used to move the contents. The 4″ diameter by 12″ length reflects the CARM's intended use in transporting a meal-size portion of edible biomass for a crew of four. The opening of the cylinder should be the same size as the container to prevent a backup of the contents at the opening.

A bag lining was needed to contain small particles. The contents of the bag were expelled by using air pressure within the cylinder to force the bag inside out. There were two important criteria for selection of the bag material: (1) flexibility for ease of transfer and (2) durability for a high number of cycles (1500 cycles/year). Several different options were considered for the bag's material: Flexiglass, polyurethane, and flexible PVC. The final selection of the polyurethane was determined by its flexibility and ease of inverting.

A vital component of the CARM is the closing of the bag attachment. This prevents particles from dispersing randomly during transport or transfer. Several different closing mechanisms were examined: a sphincter, an iris, and a hinge.

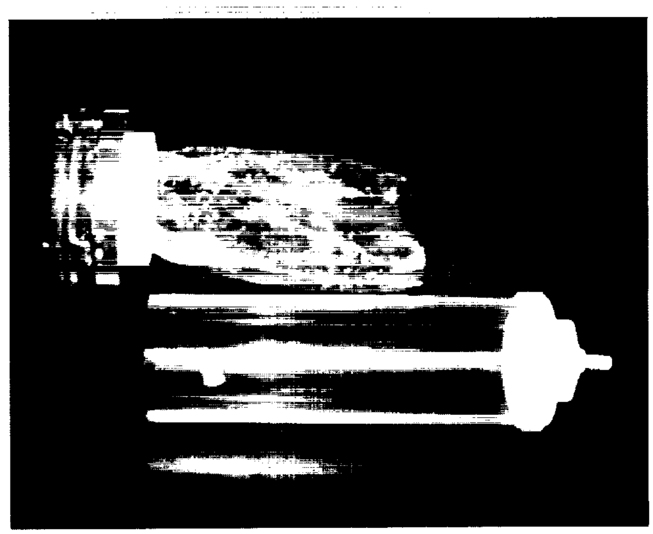

Fig. 5. Container and receiving mechanism (disassembled).

A modification of the iris is the snare end effector in the mechanical arm of the shuttle. This system consists of three wires arranged equidistant from each other on an outer ring attached transversely to an inner ring. The wires system works by rotating the outer ring while keeping the inner fixed. This twists the bag closed. This system has proved effective in containing small particles such as flour.

In order to substantiate the CARM working in a microgravity environment each test was run at multiple orientations. The use of multiple orientations assumes that if the CARM can work in opposition to gravity, then a microgravity environment will not adversely affect the CARM's performance. Testing of the CARM involved two separate procedures. The first experiment involved the complete sealing of a CARM unit without loss to the surroundings. The second, more challenging, experiment involved minimizing the loss to less than 1% during transfer from one CARM to another.

The first step was eliminating loss of the contents during transport from one area to another (Fig. 6). The zero-loss seal of the CARM unit was accomplished by using the modified iris design. Complete sealing was necessary to enable the CARM to be used as a storage unit. Without a tight closure to prevent the passage of air or moisture the food contents would spoil.

During transfer of the edible biomass from one CARM to another there are two specific types of loss: (1) the first loss introduced is from the junction of one CARM with the other and (2) the second loss introduced is from the residue left on the bag. Testing of the CARM prototype showed that there were no losses to the environment; however, when transferring small particles (i.e., flour) there was some residue left inside the bags.

CARM could prove a beneficial addition for long-term space missions. Its use should not be limited to transport and storage of edible biomass. With the development of CARM units in a variety of sizes, CARM has limitless possibilities. It can be used in planting and harvesting to deliver seeds and remove harvested crops. CARM's applications extend to resource recovery where it can be used between bioreactors. CARM could be used to transport from the crew compartment throughout the BMS.

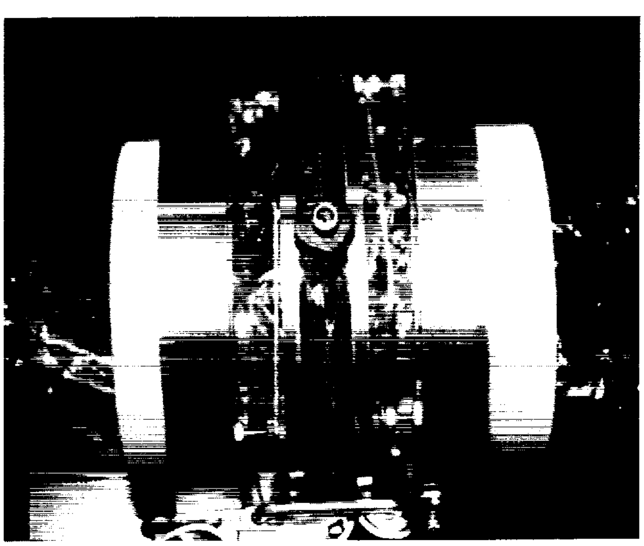

Fig. 6. CARM interlock with another unit for transfer.

Fig. 7. Air curtain device for fugitive particle control.

AN AIR CURTAIN SYSTEM FOR FUGITIVE PARTICLE CONTROL

In a microgravity environment fugitive particles from foodstuff, for example, can migrate and lodge on surfaces. Control of such debris plays an important role in the health of the crew and the functioning of equipment. In the Biomass Management System investigated by this class last semester, several subsystems could greatly benefit from the existence of fugitive particle control devices. For example, food preparation involves the transfer and processing of biomass that should be contained in specific regions.

Different systems to control fugitive particles were explored by this team. Of all the systems investigated, an air curtain (Fig. 7) was found to be the most promising solution for particle control. Air flow characteristics of different configurations were investigated and a system consisting of a single air curtain was selected for further development.

The main concern of this team was the effect of the arms through the air curtain, since it was suspected that this could disrupt the flow of air. To prevent debris from escaping or entering through the stagnation point created by the flow around the user's arms, a suction accessory was integrated at the bottom of the unit. The blowers and motor, which generate the air curtain, were installed behind the unit to allow frontal visibility. The sides and top are made of clear plexiglass to allow visibility into the device. To preclude the necessity of air separators, a plenum chamber was incorporated in the design. The nozzle was lengthened to create a more laminar flow. A method was designed to recycle the air back to the intake of the blowers. This method took advantage of the suction created by the blowers. A filtering system was incorporated into the design.

For testing of the device, small styrofoam particles of approximately 1/8 in (5 mm) diameter were put inside the unit

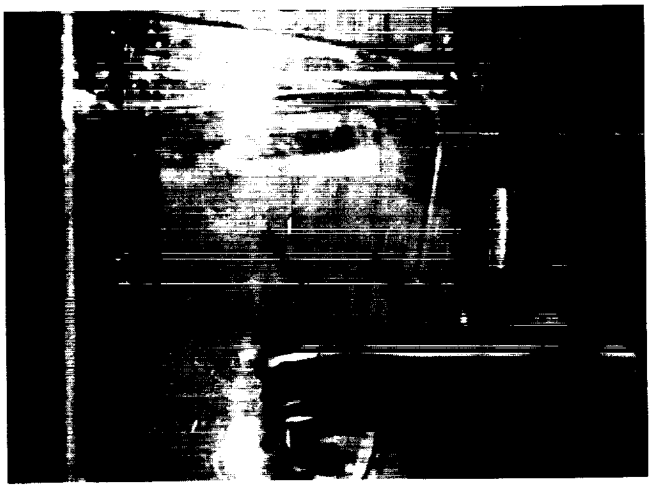

Fig. 8. Air curtain device in operation.

(Fig. 8). A hand-held fan placed inside the unit was used to disturb the particles. It was observed that the particles were successfully controlled by the device. These fugitive particles either (1) stayed in the working area or (2) were removed into the filtering system when attempting to escape. The nozzle output was 400 cfm at all points along its horizontal axis. The volume at the suction was 510 cfm. This volume increase was accomplished by increasing the area of the intake. The filtering system successfully trapped the fugitive particles for later disposal into the vacuum device.

Fugitive particle control is a major concern for long-term space missions. It was found that a single air curtain system would be effective in preventing particles from entering or exiting working areas. The prototype unit successfully controlled fugitive particles. The unit was found to successfully contain or expel low-density particles (i.e., bread crumbs) traveling at 218 ft/min (1.11 m/s) perpendicular to the curtain. The results suggest that the single air curtain configuration will be useful in containing fugitive particles from escaping or entering a work area in a microgravity environment. The unit was self supporting, i.e., the air curtain and the suction device were one single mechanism. The technology for the implementation of air curtains for fugitive particle control is readily available and units can be easily built to fit the desired function.