Apr 29th, 1:00 PM

Paper Session III-B - Development of a Microgravity-Rated Hydroponic Plant Culture Apparatus

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DEVELOPMENT OF A MICROGRAVITY-RATED HYDROPONIC PLANT CULTURE APPARATUS

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Abstract

Porous tubes provide a novel means of growing plants hydroponically under conditions of microgravity. The experimental strategy for a spaceflight experiment utilizing this technology (anticipated in the 2000-2001 timeframe) is presented. The primary question to be addressed relates to the control of optimal rates of water provision, and how it can be expected to differ between the spaceflight and earth-based environments.

Background Information

NASA seeks to utilize plants to recycle air, water, wastes, provide food and contribute to the psychological well being of the crew during prolonged spaceflight missions. Unfortunately, among those investigators who have grown plants in space, none to our knowledge would claim to have achieved optimal conditions for plant growth. We believe that the provision of adequate levels of water (without causing water logging) and oxygen to the root zone are the most crucial components deterring major advancements in this area. The dominance of the surface tension of water under microgravity conditions has often been found to lead to either severe water-logging or excessive drying in the root zone. Consequently, differences in plant growth responses between spaceflight experiments and their ground controls are expected based merely upon differences in moisture distribution patterns between the two conditions (Levine and Krikorian, 1996). Until we have a better means of controlling these critical aspects of plant culture, all differences determined by investigative endeavors will be called into question as to whether they are related to "direct" effects of microgravity or merely "indirect" effects attributed to a microgravity-altered culture regime. The latter produces results less optimal than if the growing conditions been better controlled to accommodate spaceflight conditions.

Current plant culture systems intended for spaceflight generally fall into two categories: (1) active nutrient delivery systems, which provide for nutrient replenishment from a remote reservoir, and (2) passive nutrient delivery systems, which either provide an initial reservoir of nutrients designed to last for the duration of the experiment or which can be manually replenished. While passive systems are intrinsically less complex in nature, and thus less prone to various causes of malfunction, active systems (if reliable) have the potential for long-term, less labor intensive plant growth, and offer a greater degree of control over nutrient solution characteristics and delivery. Whatever approach is used, it must be safe, cost-effective, and reliably provide optimal conditions for the growth of plants under the unique conditions of spaceflight. It is our belief that these objectives can best be met by the use of a microgravity-rated hydroponic plant culture apparatus. This capability does not currently exist, but has been repeatedly requested by the plant science community.

The case for space-based applications of hydroponic nutrient delivery systems has been made (Knight, 1989; Schwartzkopf, 1990; Tibbitts, 1991; Brooks, 1992). The advantages of hydroponics are as follows. The use of soil, or any substrate, can be eliminated, which avoids problems associated with soil-borne diseases. This is particularly relevant as concerns have been raised regarding microbe-related problems associated with nutrient delivery approaches based upon reusable substrates (Levine, in press; Bishop et. al., 1997). This point becomes

more critical given the nature of a long duration spaceflight mission to Mars where several generations of crops (and associated microbes) will be propagated within a closed habitat in close proximity to the crew. Hydroponic systems are routinely cleaned and sanitized between plant harvests, and any disease problems which may arise are more readily eradicated by the addition of exact sanitizing treatment concentrations to the liquid nutrient medium (there not being any untreatable refugia within the nooks and crannies as in a particle-based rhizosphere). The hydroponic approach has been associated with minimizing much of the labor associated with traditional plant culture (tilling, watering, fumigating, etc.), and it provides the potential to maximize yields while conserving water and nutrients. By its very nature it permits a more complete control of the plant cultivation environment given that the elemental composition of the nutrient solution can be completely defined and precisely controlled on a real time basis. This advantage permits the hydroponic approach to greatly facilitate the monitoring of plant nutritional state, and also facilitates a more precise tracking of the water budget through the system. The water has to be either in the system's plumbing, in the plants or in the atmosphere, whereas in other approaches there is a large amount of untracked water in rhizosphere particulates.

Conventional hydroponic systems possess open solution surfaces and are dependent upon gravity to direct solution flow. Both of these properties preclude their use under conditions of microgravity. The Porous Tube Plant Nutrient Delivery System (PTPNDS) has been specifically developed to overcome these challenges (Dreschel, 1990). In this approach roots grow directly on the surface of porous tubes through which a nutrient medium is circulated (Figures 1, 2, 3).

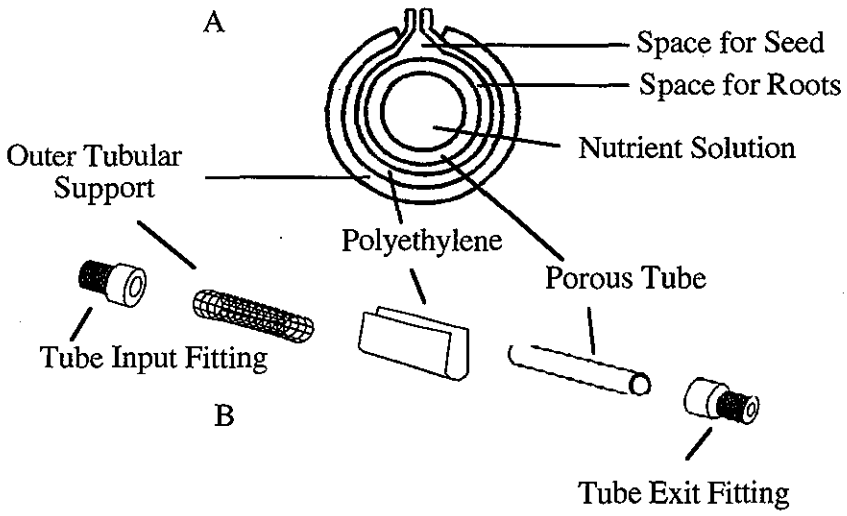

Figure 1. A. Cross sectional view of a porous tube configuration. B. Exploded view showing the individual system components.

Challenges for fluid delivery in space include preventing free liquid from escaping the rooting zone, providing a uniform distribution of water and nutrients within the root zone, and maintaining adequate oxygen levels for root respiration. By its very nature, the porous tube technology minimizes problems related to a lack of oxygen in the rhizosphere. Roots surrounding the tubes are encompassed by an air space which is contained within an outer root barrier (Figure 1). Thus, not only is there a constant supply of oxygen in immediate contact with the roots, but the potential for water logging is greatly reduced. This has been demonstrated by a series of studies in which the PTPNDS was compared with agar-based and floral foam plant culture systems developed for spaceflight applications. In these investigations alcohol dehydrogenase (ADH) levels in the roots were used to indicate water logging (oxygen-deprivation) stress. Of the systems tested, the PTPNDS grown plants produced the lowest amount of ADH in their roots and the highest shoot biomass, indicating the lowest level of stress (Porterfield, 1996; Porterfield et. al., 1997).

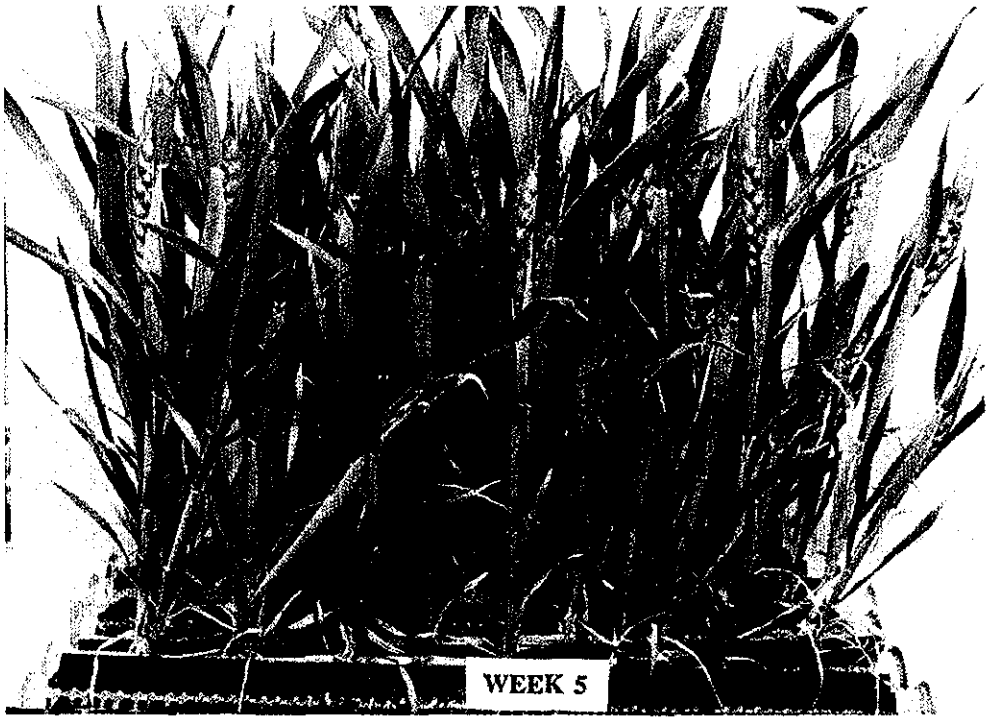

Figure 2. A representative picture of forty-five wheat plants grown for five weeks on porous tubes. Seed heads are visible.

Figure 3. A close-up of the base of the Figure 2 wheat plants as initiated within foam blocks on top of a porous tube. A slice has been made along the root mass revealing the tube beneath.

Extensive ground-based studies (Dreschel et. al., 1992) have demonstrated the ability of the PTPNDS to support various crop plants, and the system can be physically controlled to function in a predictable manner under altered gravity conditions ranging from microgravity on the NASA KC-135 to hypergravity of up to 2 g on a centrifuge (Dreschel et. al., 1993; Tsao et. al., 1996). It has also been used as a research tool to evaluate the response of plants to varying degrees of water and nutrient stress (Dreschel et. al., 1989) and to investigate the hydrotropic response of plant roots to moisture gradients (Takahashi et. al., 1992). Other potential uses for this system are for growing plants under conditions in which water conservation is critical in as the water and nutrient solution is fed directly to the roots of the plants, thereby minimizing excess water which would be lost through evaporation (Dreschel and Sager, 1989).

Experimental Plan

We have learned through experience that despite numerous successful trials in the laboratory, the only valid confirmation of a microgravity-rated plant culture system can come from a demonstration of its performance in space. Procedures that are routine on Earth need to be made reliable under the novel and still poorly defined conditions of microgravity. We have therefore proposed and been selected to undertake a porous tube spaceflight experiment (of 5-16 day duration) within the 2000-2001 time frame. We will address the question of "comparability of environmental conditions" between the flight and ground control experiments by employing three different porous tube pore sizes at one preset water delivery system pressure setting. It is anticipated that different pore sizes (for any one given control pressure set-point) than those used on Earth will be required to support optimal plant growth in space. Once this relationship is determined, the scientific community will be able to focus their efforts on a diverse array of research questions (made possible by this microgravity-rated hydroponic system) without concern for superimposed complications relating to unknown variations in water/nutrient delivery rates. In short, we wish to quantify the effects of solution pressure and pore size on plant growth in the microgravity environment in order that we can optimize the root environment for growing plants in space.

A spaceflight-rated version of the PTPNDS has been constructed and assigned the acronym of MPNE (Microgravity Plant Nutrient Experiment; Figures 4, 5). MPNE is a single mid-deck locker payload which consists of a sealed plant chamber containing three porous tubes, a computer which controls and tracks all activities, and a video camera which records the (time-lapsed) growth of the plants during experiments.

We recognized early on that one of our largest challenges relates to the ease with which reliable seed germination could be achieved in space. Both on Earth and in space, a specific moisture range is required for optimal seed germination. If seed-containing wicking units become either too dry or too wet there is a significant reduction in germination success. Given an optimum moisture level set-point for operation of the MPNE apparatus on Earth, there remains some question as to whether this 1 g set-point would be appropriate for operation on orbit. We therefore developed a seed holding methodology which extends the moisture "window" (on both the lower and upper ends) for successful (automated) seed imbibition and germination on-orbit using the MPNE hardware (Figure 6; Levine and Piastuch, accepted). We will continue ground studies aimed at refining our seed germination techniques to make them as resilient and resistant to non-optimal water delivery regimes as possible. Several "open" cassette designs are envisioned which will allow air to reach all parts of the seed while maintaining a thin film of moisture around the seed. Additionally, we will evaluate a range of materials for their wicking and seed compatibility characteristics.

For the spaceflight experiment, dry seeds will be loaded three days prior to Orbiter lift-off, and the system will be initiated by the crew on-orbit. The fluid circuit will be filled by the water delivery system and the porous tubes purged of air. We have proposed to imbibe and germinate a minimum of 72 wheat (*Triticum aestivum*) seeds on orbit with a plant chamber temperature of 25° C, 80% relative humidity, and a 16:8 light/dark cycle. Time-lapsed video recording of the plants will allow for growth rate determinations over time.

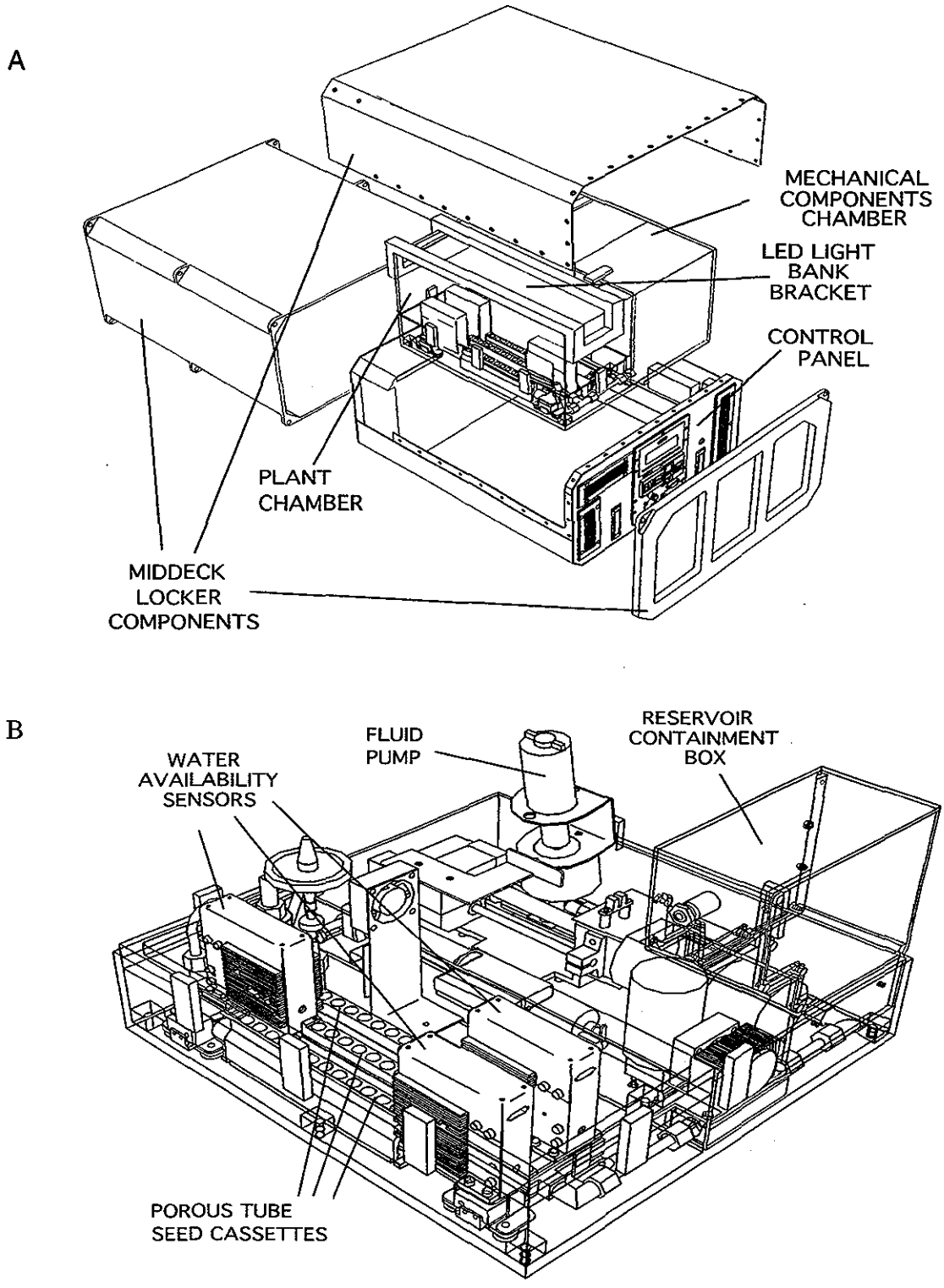

Figure 4. Microgravity Plant Nutrient Experiment (MPNE) hardware drawings: A. Exploded view of Shuttle middeck locker within which the MPNE apparatus resides. B. MPNE internal components.

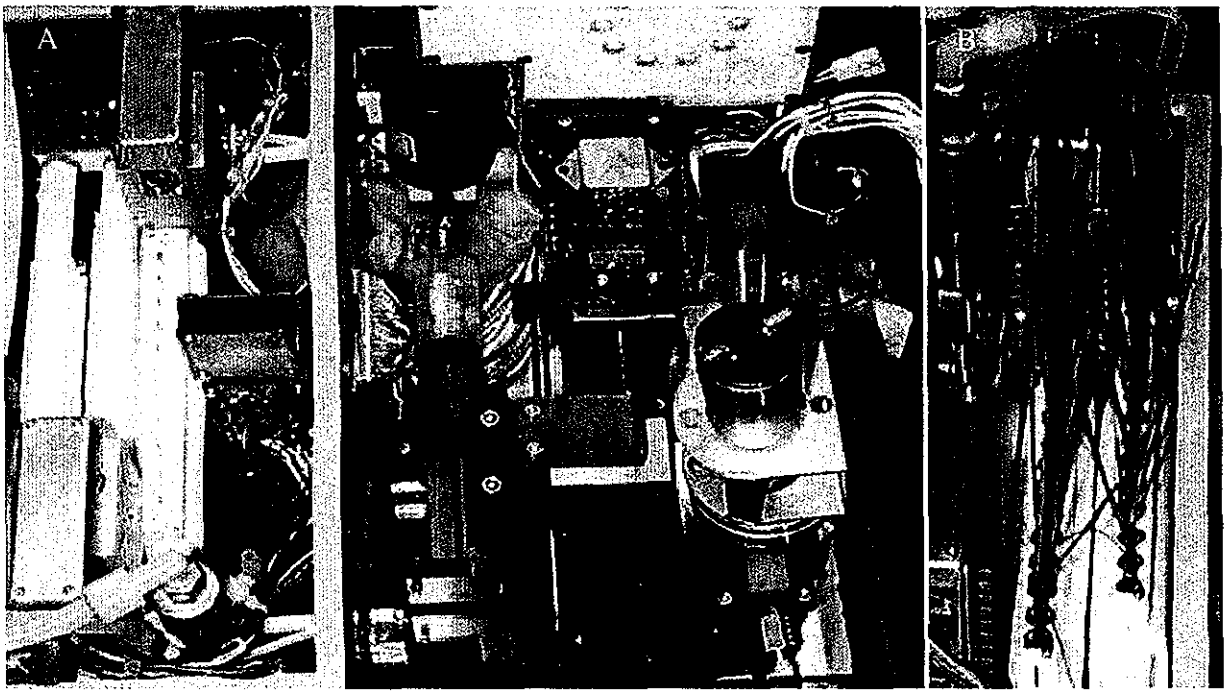

Figure 5. (A) Top View of the MPNE hardware with the light cap removed from the plant chamber containing the three porous tubes (left) and the syringe pump and various system control mechanisms visible on the right. Note that one of the three porous tubes has its seed casset in place around the tube and is ready for seed cylinder insertion. (B) View of plants after a seven day experimental run. The seed cylinders (each containing two wheat seeds) can be seen to be contained within the seed casettes which encompass the porous tubes.

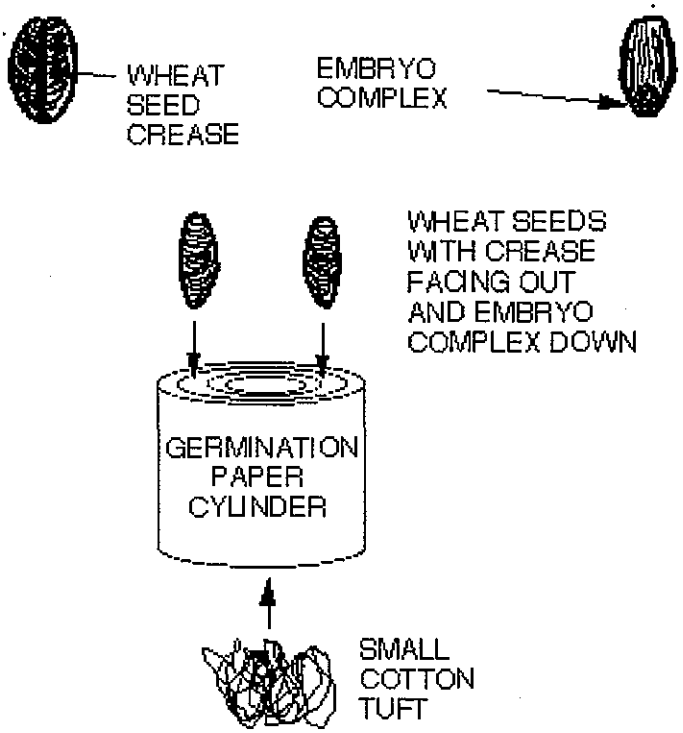

Figure 6. Diagrammatic representation of the germination paper seed cylinder configuration. Wheat seeds are placed into the peripheral region of the cylinder with the embryo complex facing downward and the seed crease facing outward. A small tuft of cotton is then inserted into the bottom crevices of the cylinder.

For the precise delivery of water it is necessary to non-invasively detect and monitor the thin-film of the nutrient solution on the surface of the porous tubes. The desired degree of wetness will vary as a function of the plant's life cycle stage. For seed germination, only the slightest amount of water will be required, and the requirement for water will increase as the plants grow. In order to achieve this objective, we will use a hydraulic pressure control system for the primary control of water delivery rate. There will be a back-up controlling mode in which nutrient solution will be delivered on a fixed-feed basis. The amount to be delivered using this latter option will be dependent upon life cycle stage.

We will need to measure the thickness of the solution on the surfaces of the tubes in order to monitor both the physical response of the different pore sized tubes and the response of the plants to these tubes under microgravity. The water monitoring system will provide a continuous record of actual tube wetness achieved on each of the porous tubes, and will be used as an input to the two wetness controlling mechanisms (pressure-based and fixed-feed mode). It is currently anticipated that the method to be used will be based upon a resistance measurement made by passing a current through a wire whose ends will be embedded at each end of the porous tubes. The level of resistance will be a function of the "wetness" of the entire tube, thus providing an integrated measurement of water thickness along the entire tube. Extensive testing will be required to "calibrate" the method.

We are proposing that the MPNE hardware be outfitted with three different (from 0.2 μm to 0.7 μm) pore sized tubes serially linked on the same fluid loop. Investigations will be required to determine a pressure set-point which will be suitable for both the spaceflight and ground control experiments. We will conduct a series of ground studies to precisely establish both; (1) the required porous tube moisture levels for our selected wheat strain from the beginning of imbibition through three weeks of growth and development, and (2) what combinations of system pressure levels and porous tube pore sizes can be used to provide these desired moisture levels.

Under the current design of this experiment it is to be expected that optimal growth will not occur in all seedlings grown on the three different pore sized tubes. Indeed, it is our hypothesis that at least one tube will provide flooded root zone conditions favorable for development of hypoxic conditions. This will provide (on earth and in microgravity) for the examination of root behavior and seedling growth under flooded and well oxygenated root zone conditions.

Conclusions

In future implementations we will incorporate additional design changes relating to the efficient handling of seeds prior to loading into the system, and ease of mass plantings by crew members. Other modifications which we envision include continuous monitoring (and adjustment) of nutrient solution pH and electrical conductivity levels plus lighting enhancements to increase intensity for optimization of plant growth and photosynthetic rate investigations. In addition, we propose to add humidity control/recycling to demonstrate conservation of water capability and to permit investigations on evapotranspiration. A real time data and video down link capability will be incorporated for better synchronization with ground control experiments and real time monitoring at a remote site. This telescience capability, i.e., control of set-points from Earth to provide real time critical decision making by the science team, will lead to optimization of science return in addition to enabling downlink video to an internet connection for educational outreach activities.

In closing, if the goals of this proposal are achieved, we believe that this technology can have a dramatic impact on the success of future space-based plant growth efforts. The technology also has the potential to reduce the amounts of power, volume, thermal control requirements, consumables, and crew-time needed for the reliable growth of plants in space. This technology can provide NASA with an early benefit in terms of fulfilling the requirements for the Transhab vegetable production unit, and could result in several spin-off applications in the areas of home-based hydroponic units and water conservation applications.

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