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# **Microgravity Root Zone Hydration Systems**

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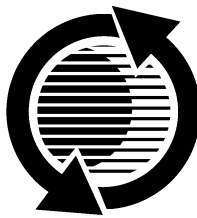
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## ROOT ZONE HYDRATION

Plants need water for photosynthesis and transport of dissolved nutrients. Water passes through the plant and is lost by transpiration, as well as evaporation from the root zone, i.e. evapo-transpiration. This reduces the water available to the plant, and changes the root zone environment such as the nutrient concentration and the pH. Water availability is typically expressed as 'water potential' ( $\Psi$ ), in units of a negative, or 'suction' pressure. A large water potential  $\Psi$  indicates a large suction pressure, i.e. lack of water. Soil saturated with water in a gravity field, for example, typically measures approximately  $\Psi = -1000$  Pa (Salisbury and Ross, 1989). A more negative number, or a larger  $\Psi$ , indicates less water available to the plants. In addition to water and nutrients, gas exchange is necessary to supply oxygen to the respiring roots and to remove released carbon dioxide, and any other potential trace gases such as ethylene, a plant growth hormone produced by the plants.

For optimum and scientifically reproducible plant growth experiments, the growth conditions should be well controlled. For plant research here on Earth, when well-controlled and reproducible root zone conditions are desired, aeroponics or hydroponics systems with accurate nutrient, pH and oxygenation control are often employed. In the microgravity environment, however, containment of water and the control of the liquid-gas interface require specialized designs.

## REQUIREMENTS

The requirements imposed on the root zone hydration system are:

- Supply appropriate nutrient concentration and composition, which may be dependent on plant age and plant species.
- Maintain desired water content or water availability to plants over their entire growth or experiment cycle.
- Adjust water supply to appropriate levels for each developmental phase such as germination, imbibing of seeds, plant growth, harvest (water recovery) and system restart.
- Allow adequate gas exchange for oxygenation,  $\text{CO}_2$  and trace gas removal to the root zone.

For relatively short sortie missions (< 16 days), most systems to date have been launched 'wet', i.e., they already contained, at launch, the appropriate water content of 70-80% of saturation. Plants had already germinated, and root-shoot orientation was not a problem. The injection of a known water volume at launch is intended to prevent water-logging or flooding. Sufficient air space and air exchange is required to prevent anoxia in the root zone. The media is soaked with nutrients at the plant-specific and appropriate concentration, and should not require any resupply

during short missions (<16 days aboard Shuttle). Hydroponics media that allow slow release of known amounts of nutrient salts are often promoted (Zeolite; Zeoponics: Steinberg et al., 1997, 2000).

Alternatively, during long missions and for repeated plant cycles aboard space stations (MIR, ISS), on-orbit germination is often desired. The root zone is launched dry with seeds in place. On orbit, either automated or through crew interaction, the media is saturated with water to the desired optimum water content for germination. Since the media is completely dry at start-up, the initial moisture content is easily controllable by injecting known quantities of water.

As plants grow and water is lost from the root zone by evaporation and transpiration, replenishment and moisture maintenance become challenging. In a sealed system, the humidity control condensate can be returned to the root zone, and a steady state can be maintained. With open systems, where moisture is lost to the crew cabin at an unknown rate, an active feedback control system of water availability becomes a necessity (see below).

At typical moisture contents of 70-80%, large quantities of water are bound in the root zone. Upon harvesting of plants, it may be desirable to retrieve that water from the root zone for future growth experiment. Depending on research objectives and plant use, retrieval of root material may also be desired. For these experiments, the root system must provide easy access for root removal without damaging the roots, or without endangering the astronauts with escaping substrate material.

## ROOT ZONE HYDRATION SYSTEMS

The following water delivery systems have been used with various degrees of success in spaceflight plant growth systems:

- Floral foam, saturated with water and nutrients (PGU, PGF).
- Solidified Agar, in gas exchange container with appropriate and layered nutrients, even radioisotope labels (PGBA, PGU: Heyenga, 1997; Kliss et al., 2000).
- Soil, of various grain size, composition and pre-loaded with customized nutrients, with and without water replenishment (PGU, PGBA).
- Hydroponics substrates, loaded with appropriate nutrients, and resupplied with water through porous tube delivery systems (AstroCulture™: Morrow et al., 1994; Goins et al., 1998, Zeoponics: Steinberg et al., 1997, 2000).
- Porous Tubes, roots growing on the outside perimeter of the ceramic or sintered metal tube (MPNE; Goins et al., 1998, Levine et al., 1998, Dreschel et al., 1993, 1994). Original flat plate design CERES (Wright et al., 1988).

## Substrate systems

Substrate systems provide an anchor for the plant, as well as water storage and transport through capillary action, and nutrient storage both in the water and in the pores of the media (ion exchange resins). The substrate material properties and especially the pore and grain size of the material, the pore size distribution and uniformity dictate its performance in microgravity. Packing density of otherwise identical substrates alter its performance dramatically. Inappropriate substrate selection may lead to inadequate water transport and distribution. Hydroponics substrates include the zeolite Balkanine (SVET aboard MIR, Ivanova et al., 1993, 1994), Arcillite (AstroCulture™: Morrow et al., 1994; Goins et al., 1998), Zeolites (Steinberg et al., 1997, 2000), soil (Figure 1) and solidified nutrient solution (agar, Figure 2, Heyenga, 1997).



Figure 1. The PGBA root zone hydration system (Hoehn et al., 1998). Media for each plant is contained in gas-permeable polypropylene bags. The bags reduce evaporation, while maintaining proper root zone oxygenation. Each bag is surrounded by airflow passage ways. The bags are resupplied from the bottom with condensate from the humidity control system (App. 1).

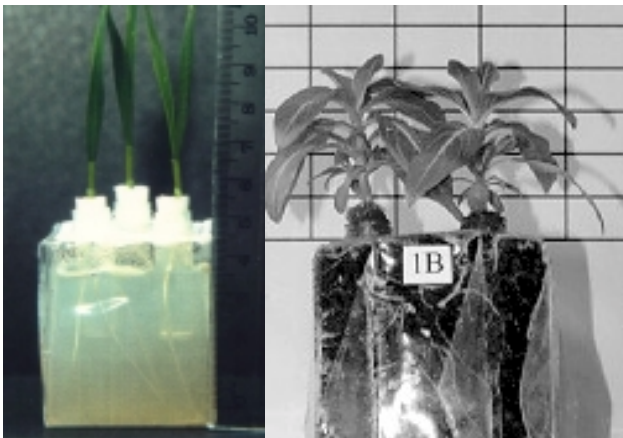


Figure 2. Nutrient Packs. Gas-permeable polypropylene membranes can accommodate a variety of soil matrices. Solidified nutrient solution agar (left) packs are typically not water-replenished to compensate for evapotranspiration losses, and support plants for up to 16 days or longer (Heyenga, 1997). When attached to a water distribution system through the bottom, the bags can be replenished with water almost indefinitely (right, Kliss et

al., 2000). Packs are surrounded by air flow in PGBA to maintain root zone oxygenation. Solidified agar packs have also been used with radioactive tracer elements or pH indicator (Heyenga et al., 1998; Heyenga, 1997).

Water transport characteristics through media change not only with grain size, but also with packaging density, which affects the pore size and pore size distribution throughout the media. This, in turn, affects the wettability of the media. Water can be injected manually by astronauts into the media, but more often is now supplied through porous sintered stainless tubes on the bottom of the substrate container (Steinberg, 1997, 2000; Goins et al., 1998). The porous stainless steel controls the gas-liquid interface, and is typically held under slight suction pressure to prevent water logging in the substrate (Dreschel, 1993, 1994). Best plant performance is typically achieved with the smallest, controllable suction pressure ( $\psi \approx -250$  Pa), limited by available sensor technology and the unavoidable gravity-driven hydrostatic pressure for Earth-based testing given the tube geometry.

## Substrate-free systems

Substrate-free systems typically used on Earth include true hydroponics (roots submerged in aerated water) and aeroponics systems (nutrient-mist, Figure 3). Neither of these systems is easily accommodated in microgravity due to lack of phase separation between the gas and liquid phase (Clawson et al., 2000).

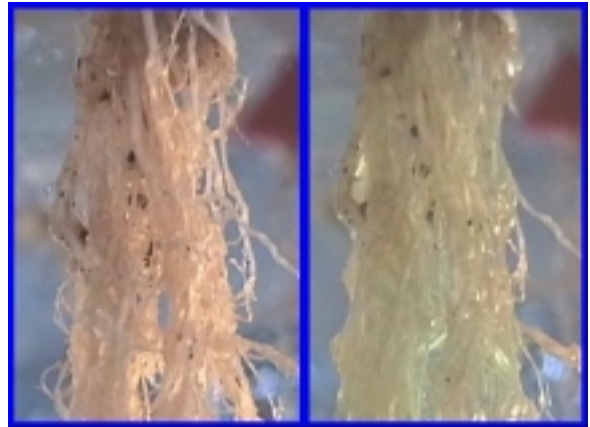


Figure 3. Hydroponics / Aeroponics test aboard KC-135 parabolic flight. Roots on left (1-g) are drained, while in reduced gravity ( $10^{-2}$ -g), water accumulates and wicks up into the roots, causing potentially anoxic / water-logged conditions.

One substrate-free system that has been tested extensively on Earth is the NASA KSC Porous Tube Plant Nutrient Delivery System, PTPNDS (Dreschel et al., 1993, 1994, Tsao et al., 1996; Levine et al., 1998). Plants are grown directly on the outside of a porous tube, typically ceramic or sintered porous metal. Water or nutrient solution is contained inside the tube, typically under a slight negative, i.e., suction, gauge pressure

when compared to the ambient gas pressure (Figure 4). Slight suction pressures of  $-250$  to  $-1250$  Pa is intended to prevent flooding, but best plant performance is achieved with smaller suction pressures (Goins et al., 1998). The porous tube restricts the root growth basically to a two-dimensional, thin root geometry around the tube, rather than the much larger, three-dimensional volume available with substrate or aeroponics systems. Water potential values  $\Psi$  customary from substrate systems are not readily translated into porous tube water delivery pressure. Surface tension on the air-inclusion-free tube, i.e., a well-primed, completely water-filled tube (Scovazzo, 1998, 2000) prevents air intrusion into the tube, allowing control of the gas-liquid interface. Hydrostatic pressure as a control variable for water availability has been successfully used to maintain the slight suction pressure of  $\Psi \approx -250$  Pa continuously for extensive ground testing. A flight experiment, Microgravity Plant Nutrient Experiment, MPNE, was designed to use Infrared Absorption, rather than pressure sensors to control water availability. On-orbit problems prevented successful plant growth (Levine et al., 1998). The Infrared Absorption sensor, called 'Water Availability Sensor' or 'WAS', is a potential technology that can be used specifically with substrate-free growth media (Dreschel et al., 1993). A future, comparative flight test between substrate and substrate-free tube delivery systems is planned (Wells et al., 2000; Levine, 1998; see also Appendix 2). Even the substrate-free PTPNDS system may require specialized seed holders to attach the seeds and to enable seed imbibitions and successful germination (Johnson et al., 1996).

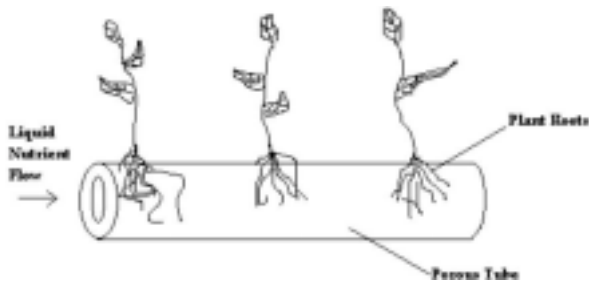


Figure 4. Schematic of a Porous Tube Plant Nutrient Delivery System (PTPNDS). Ceramic or sintered stainless steel tubes of 12 – 50 mm diameter are typically used, with pore sizes of 2 – 20  $\mu\text{m}$ . The smaller the pore size, the larger the bubble pressure. Pores are smaller than the root diameter to prevent root intrusion.

## SUBSTRATE SELECTION

Predicting and testing microgravity performance of a substrate is hindered by lack of frequent on-orbit testing capacity. Often, a system is designed and tested under Earth gravity conditions, and short periods of reduced gravity testing during parabolic flight with  $\approx 20$  second long test periods. Parabolic flight tests are typically too short for conclusive results. Under Earth gravity, actual microgravity fluid redistribution and potential problems such as flooding cannot be easily predicted.

Since water distribution and air exchange behavior on orbit cannot be simulated on Earth, investigators have often attempted to measure surrogate parameters during laboratory and parabolic flight testing. One parameter typically measured is the capability of a substrate to wick water, and how uniformly water spreads throughout the media. Additionally, the wettability of the media can be tested. Wettability typically changes over time and repeated use, and can be affected by surfactants in the water or pre-treatment of the media.

The use of these indicators may not be appropriate for all phases of plant growth. The capacity of a media to be wetted and to uniformly wick water may be of great importance to the initial priming, or initial filling with water, and seed germination, but has very little impact on how a substrate behaves in transporting water under steady state, i.e., once primed. A poorly wicking and wetting material may be a perfect water transport media, sustaining high water flux rates once properly primed (Scovazzo, 1998, 1999, 2000).

## Unsteady Wetting and Wicking Tests

The dry media is brought in contact with water, by either injecting water at a certain location, or immersing the media into water. The dynamic response of water moving through the media or along the media surface can be observed. Measuring the height of water traveling against a gravity gradient is used as another easy, but potentially misleading criteria. A good wicking and wetting media may be too hydrophilic and may cause gas exchange problems once in microgravity. Wicking and wetting tests, however, are good indicators for how well dry seeds in a dry media may be exposed to uniform conditions for germination. Some media are initially coated with a wetting agent (floral foam, Rockwool™). After continued use, or if the media dries out, the wetting agent may be depleted. A plant-compatible surfactant can be added to the water (Osmocote™), or the media has to be re-coated. Difficulty to initially wet a dry material does not necessarily mean the media is a poor growth media, as it may be a good water transport media once primed (see below). Wetting tests can also be performed during parabolic flight tests, as time constants are compatible with the approximate 20-25 seconds of reduced gravity. It has to be emphasized that these unsteady wetting and wicking tests, simple and easily performed, do not predict the performance under steady state plant growth conditions, and a good wetting material may lead more easily to water pooling or flooding.

## Steady State Water Transport Test

Some media used in spaceflight to date may prove to be difficult to wet, yet once primed, they perform very well to maintain a constant moisture content and transport water throughout the matrix as the plant roots take up water. To test the water transport capability, the media is fully

primed by soaking or submerging in water, the addition of surfactants, or coating with a wetting agent prior to water exposure. Supplied with water from one end, the 'bottom' for tests on Earth, and evaporation from the opposing end, enhanced by air flow on top, different media can be compared based on their water transport characteristics. The steady state water transport tests operate for longer time scales, and are typically not suited for reduced gravity parabolic flight-testing due to inadequate time constants, but describe the actual performance requirement of a plant growth media.

### Nutrient Delivery

As mission duration increases, and if evapo-transpiration water is returned to the root zone as 'distilled' water from the humidity control system, the nutrient concentration and composition may change over time. Slow-release ion exchange matrices, zeolites, can enhance the usable time for a root zone assembly. The use of Zeoponics facilitates the water delivery control system by avoiding the higher salinity environment of circulating nutrient solution of  $\approx 2,000$  mS/cm electric conductivity (EC).

### CONTROLLING SOIL MOISTURE

Several methods have been tested and tried to control the amount of water available to the plants, while also providing adequate gas exchange and preventing flooding. These include active moisture sensor feedback to control the amount of water in the matrix, or passive control of water availability, where the plants provide the forcing function to 'pump' water as needed by capillary action. Pressure control in the porous tube delivery system surrounded by a substrate can be used indirectly to control the soil moisture (Tsao et al., 1996; Steinberg et al., 1997).

### Moisture Sensor Feedback

Several sensors to measure soil moisture have been tried:

- heat pulse sensor – Figure 5. Based on concept that a higher water content changes the heat capacity of the surrounding media; Reece, 1996; Shaw et al., 1939; Meek, 1999; Clark et al., 1994).
- infrared absorption (more water absorbs more IR-light – Water Availability Sensor, WAS; Dreschel et al., 1993).
- electric conductivity (more water provides more electric pathways; Shaw et al., 1992).

Measurement of soil moisture is difficult, as each of these sensors is affected by a variety of additional variables, in addition to the water content:

- density and heat capacity of matrix
- packing density of matrix in root container

- particle size, wicking and wetting characteristics.
- electric conductivity (nutrient composition)

Heat Pulse Sensor: The packing density of the soil and its heat capacity, the contact between the sensor and the soil matrix, and the root content around sensor all affect the thermal conductivity and the heat capacity. Changes due to water content may very well be masked, and custom calibration may be necessary (Meek, 1999). Launch vibration loads could change, for example, the packing density and the contact between sensor and soil matrix, invalidating previous calibration.

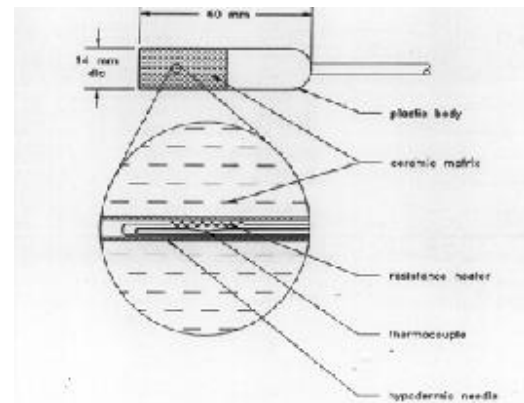


Figure 5. Heat pulse sensor for soil moisture measurement (Meek, 1999). A thermistor and resistor are embedded inside a ceramic contact material, which is embedded in the soil matrix. The resistor (heater) is turned on for several seconds. The resulting temperature increase, measured by the thermistor, depends on the thermal conductivity and heat capacity of the surrounding material, which is dominated by the water content, and can be related / calibrated to soil moisture.

### Water Availability

Controlling water availability in spaceflight substrates typically involves the control of water pressure inside a porous tube or plate, which is in contact to a soil matrix or the roots themselves. The porous tube controls the gas-liquid interface. The pressure inside the porous tube is held slightly below ambient pressure (suction) to prevent flooding of the root zone. The water is transported from the porous tube against the pressure gradient by capillary action to the roots. In case of the NASA KSC Porous Tube System (Dreschel et al., 1994), roots grow directly on the porous tube without any soil matrix, while the WCSAR AstroCulture™ (Morrow et al., 1994) and the Orbitec BPS system use a soil matrix around the porous tubes (Steinberg et al., 1997; Goins et al., 1997). The BioServe PGBA system (Hoehn et al., 1998) uses porous plates in contact with a soil matrix to contain the water. The suction pressure within the delivery system prevents flooding. Positive delivery pressure would force liquid through the tubes / plates. If the resulting flow rate is still lower than the water uptake rate of the plants, flooding can be prevented.

The delivery pressures (suction) necessary for optimum growth of the plants are typically less than  $\approx -1250$  Pa. The NASA KSC porous tube system has currently no nutrient buffer, and therefore, the tubes have to contain nutrient solution. This allows for the potential to accurately control the nutrient solution composition (pH, EC), but requires compatibility of all components (pumps, sensors, delivery systems) with the salinity of the solution. Over time, salt may build up and disable the system. Other problems, for example, include finding pressure sensors, which are sensitive enough to measure pressures well below 1250 Pa in a saline environment, small, lightweight, and pass the scrutiny of spaceflight requirements, while proving compatibility with the salinity of the nutrient solution.

### Moisture Control

Starting from a dry root zone, plant growth can be initiated with imbibing (100% saturation with water). After a short 'soaking' period, the water content has to be reduced for germination to allow gas exchange. Too much water will prevent germination (Johnson et al., 1996). After completion of germination, the water supply typically increases over time as the plant grows. At harvest, water recovery from the root zone may be necessary.

Water addition to a dry system is probably the easier task, but uniformity of water distribution throughout the media may be a challenge. Positive displacement metering pumps (gear, piston pump, peristaltic pumps) allow for accurate control of initial water quantity, if the media is primed from a dry state. The media properties (wetting, porosity) as well as the water distribution system (porous tube, matrix) need to guarantee uniform transport throughout the media.

Active reduction of moisture from within the root matrix can be more demanding and may lead to failures. The porous tube delivery systems can apply a negative pressure (suction), and as more suction is applied, the moisture content and water availability to the plants is reduced. However, if the delivery system (porous tube) is not completely primed (air-free), if a leak has developed during launch vibration loads, or if dissolved gases come out of solution, the reduction of soil moisture, and therefore soil moisture control, may fail. As air is 'sucked' into the porous tube delivery system, volumetric metering of the moisture content is disabled.

### Pressure Control in Porous Tubes

Surface tension controls the gas-liquid interface. The smaller the pore size, the larger the bubble pressure. The largest pore in a sintered porous tube or plate system dictates the bubble point of the entire system, therefore highly uniform material is required. The pressure can be estimated based on the pore size by  $P = 2 * \sigma / r$ , with  $r$  = pore size (example:  $2 \mu\text{m}$ ),  $\sigma = 72$

dyne/cm:  $P = 72,000$  Pa (10.2 psi). See Table 1 for sintered stainless steel porous plates. See also App. 3.

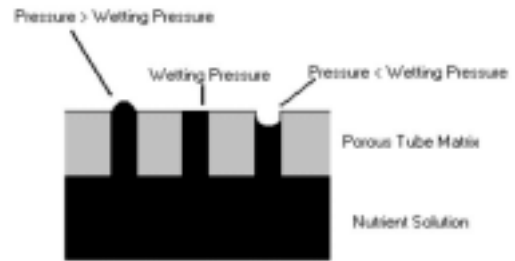


Figure 6. Pressure control in porous tube (see also: Tsao et al., 1996). A 'perfectly' wetted tube (no air inclusions) allows the control of the gas liquid interface. If the suction pressure between inside of tube and ambient pressure exceeds the bubble point of the membrane, air will enter, and the system typically will fail.

Table 1. Bubble pressure for sintered stainless steel membranes of different pore sizes. A fully primed (water-filled) membrane under suction pressure will let air pass once the bubble pressure is exceeded.

Pore [um]	Bubble Pressure				
	in HG	in H2O	psi	Pa	atm
0.2	5.60	76.16	2.7507	18971.5	0.18723
0.5	2.60	35.36	1.2771	8808.2	0.08693
1.0	2.35	32.00	1.1558	7971.2	0.07867
2.0	1.60	21.70	0.7838	5405.5	0.05335
5.0	1.21	16.50	0.5959	4110.2	0.04056
10.0	0.68	9.20	0.3323	2291.7	0.02262
20.0	0.40	5.50	0.1986	1370.1	0.01352
40.0	0.26	3.50	0.1264	871.9	0.00860
100.0	0.07	0.90	0.0325	224.2	0.00221

### Priming and Priming Maintenance

To fully prime the system, i.e., to remove ALL air from the water distribution system (porous tube system), several techniques can be employed, but not all can be easily performed on orbit or automated. Priming by water immersion, pretreatment with a wetting agent or using water soluble carbon dioxide (Scovazzo et al., 1997, 2000) can be employed on Earth in the laboratory. Priming can be aided by a de-aeration device, or bubble trap. The initial water-air mixture is pumped past a hydrophobic membrane or a centrifugal separator, where air bubbles can be removed by suction across the membrane (Figure 7).

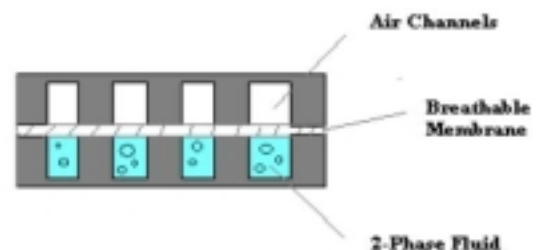


Figure 7. Bubble trap / de-aerator test bed. A pressure gradient across a hydrophobic membrane, together with

shallow channels to enhance contact probability of air bubbles with the membrane, are used to remove air bubbles from the nutrient or dehumidification liquid flow. Also used for priming the system.

### Bubble Trap

The small flow rates in nutrient delivery or dehumidification typically do not allow for sufficient velocities to implement centrifugal phase separator designs. Instead, stationary hydrophobic membranes can be employed in conjunction with a pressure gradient to remove air bubbles and dissolved gases from the water phase. A typical design can be seen in Figure 8. The small water channel thickness enhances probability for contact between air bubble and membrane. Initial performance and efficiency (% bubbles removed) are promising, but extended use deteriorates membrane performances due to biofilm formation, water saturation and membrane breakdown (Scovazzo, 1997, 1998).

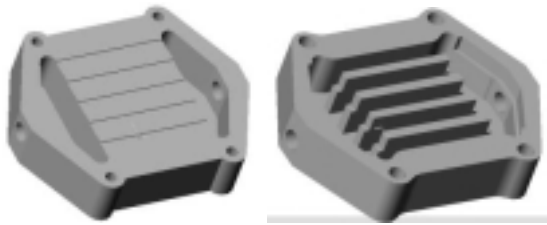


Figure 8. Bubble trap housing. The shallow channels (left) are the water side. Cross section of channels is equal to inlet line cross section area.

### **CONCLUSION**

Nutrient and water supply for short term spaceflight missions have matured and have been used successfully for up to 16 days aboard the Space Shuttle, and for up to 3 months aboard MIR. Automated and autonomous delivery systems still have to prove their functionality for extended periods in space. Employed membrane systems for phase separation may be unreliable for long duration application due to performance degradation. Currently, there is a lack of easily implemented and reliably usable sensor systems that could provide information on moisture content and nutrient concentration and water availability. Difficulties with sensor systems and engineering solutions prevent the implementation of reliable feedback control systems for microgravity.

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### **REFERENCES**

1. G.J. Clark, G.E. Neville Jr., T.W. Dreschel (1994): "A Root Moisture Sensor for Plants in Microgravity". *Adv. Space Research*, Vol. 14(11), pp. (11)213-216.
2. J.M. Clawson, A. Hoehn, L.S. Stodieck, P. Todd, R.J. Stoner (2000): "Re-examining Aeroponics for Space Flight Plant Growth", 30<sup>th</sup> ICES. SAE paper in print.
3. T.W. Dreschel, C.S. Brown, W.C. Piastuch, C.R. Hinkle, W.M. Knott (1994): "Porous Tube Plant Nutrient Delivery System Development: A Device for Nutrient Delivery in Microgravity". *Adv. Space Research*, vol. 14(11), pp. (11)47-(11)51.
4. T.W. Dreschel, C.W. Carlson, H.W. Wells, K.F. Anderson, W.M. Knott, W. Munsey (1993): "Physical Testing for the Microgravity Plant Nutrient Experiment". Proceedings, ASAE/CSAE, June 1993, ASAE-paper 93-4007.
5. G.D. Goins, N.C. Yorio, H. Vivenzio (1998): "Performance of Salad-Type Plants Using Lighting and Nutrient Delivery Concepts Intended for Spaceflight". 28<sup>th</sup> ICES, SAE paper 98-1554.
6. G.D. Goins, H.G. Levine, C.L. Mackowiak, R.M. Wheeler, J.D. Carr, D.W. Ming (1997): "Comparison Studies of Candidate Nutrient Delivery Systems for Plant Cultivation in Space". 27<sup>th</sup> ICES, SAE paper 97-2304.
7. A.G. Heyenga, M.H. Kliss, A. Hoehn, L.S. Stodieck (2000): "The Design of a Mechanized Seed Sowing System for Space Flight Application", 30<sup>th</sup> ICES 2000, SAE-paper in print.
8. A.G. Heyenga, A. Hoehn and L.S. Stodieck (1998) "A Review of Plant Experiments Supported by the Astro/Plant Generic Bioprocessing Apparatus on MSL-1", Microgravity Sciences Laboratory-1 - One Year Report, Huntsville, Alabama, August 25-26, 1998.
9. A.G. Heyenga, A. Forsman, L.S. Stodieck, A. Hoehn, M.H. Kliss (2000). "Approaches in the Determination of Plant Nutrient Uptake and Distribution in Space Flight Conditions". In: *Adv. Space Research*, vol. 26(2), pp. 299-302.
10. A.G. Heyenga (1997): "The Utilization of Passive Water and Nutrient Support Systems in Space Flight Plant Cultivation and Research". In: *ESA-SP-400*.
11. A. Hoehn, J. Clawson, A.G. Heyenga, P. Scovazzo, K.S. Sterrett, L.S. Stodieck and P.W. Todd (1998): "Mass Transport in a Spaceflight Plant Growth Chamber". 28<sup>th</sup> ICES, SAE paper 98-1556.
12. A. Hoehn, D.J. Chamberlain, J.M. Clawson, S.W. Forsyth, D.S. Hanna, M.B. Horner, P. Scovazzo, K.S. Sterrett, L.S. Stodieck,

- P.W. Todd, A.G. Heyenga, M.H. Kliss (1997): "On-Orbit and Ground Performance of the PGBA Plant Growth Facility". 27<sup>th</sup> ICES, SAE paper 97-2366.
13. T.N. Ivanova, Y.A. Bercovich, A.L. Mashinskiy, G.I. Meleshko (1993): "The First "Space" Vegetables Have Been Grown in the "SVET" Greenhouse Using Controlled Environmental Conditions", In: Acta Astronautica, Vol. 29(8), pp. 639-644.
  14. T. Ivanova, S. Sapunova, I. Dandolov, Y. Ivanov, G. Meleshko, A. Mashinsky, Y. Berkovich (1994): "SVET Space Greenhouse onboard Experiment Data Received from MIR Station and Future Prospects". In: Adv. Space Res., vol. 14(11), pp. 343-346.
  15. C.F. Johnson, T.W. Dreschel, C.S. Brown, R.M. Wheeler (1996): "Optimization of Moisture Content for Wheat Seedling Germination in a Cellulose Acetate Medium for a Spaceflight Experiment". Adv. Space Research, Vol. 18(4/5), pp. (4/5)239-242.
  16. H. Levine (1998): "Development of a Microgravity-Rated Hydroponic Plant Culture Apparatus". NASA proposal 98-HEDS-01-036.
  17. H. Levine, W.C. Piastuch, and T.W. Dreschel (1998): "Development of a Microgravity-Rated Hydroponic Plant Culture Apparatus". Dynamic Corporation, Kennedy Space Center, FL.
  18. H. Levine, B. Wells, K. Anderson, W. Piastuch, J. Moyer, W. Knott, G. Etheridge (1998): "Microgravity Plant Nutrient Experiment MPNE-01 Flight Report". Kennedy Space Center, FL.
  19. D. Meek (1999): personal communication, Applications Engineer, Campbell Scientific, Inc., 815 West 1800 North, Logan, UT 84321-1784. Phone: 435-750-9555. Model 229-L matric potential sensor (miniature heat dissipation sensor, embedded inside a hypodermic needle). For explanation, see also: (<http://parker.ou.edu/~jbasara/229l.html>)
  20. R.G. Morrow, R.J. Bula, R.J., T.W. Tibbitts, W.R. Dinauer (1994): "The ASTROCULTRE™ Flight Experiment Series, Validating Technologies for Growing Plants in Space". Adv. Space Research, vol. 14, pp. 29-37.
  21. C.F. Reece (1996): "Evaluation of a Line Heat Dissipation Sensor for Measuring Soil Matric Potential". Am. J. Soil Sci. Soc., vol. 60, pp. 1022-1028.
  22. Salisbury and Ross (1989): "Plant Physiology", 3<sup>rd</sup> edition, Wadsworth Publishing Company.
  23. P. Scovazzo, A. Hoehn, and P. Todd (2000): "Methods for Saturating Rigid Porous Membranes with Water". American Laboratory. In print.
  24. P. Scovazzo, A. Hoehn, and P. Todd (2000): "Membrane Porosity and Hydrophilic Membrane-based Dehumidification Performance". Journal of Membrane Science, vol. 167, pp. 217-225, 2000.
  25. P. Scovazzo, J. Burgos, A. Hoehn, and P. Todd (1998): "Hydrophilic membrane-based humidity control". J. Membrane Science, vol. 149, pp. 69-81.
  26. P. Scovazzo, A. Hoehn, P. Todd, J. Burgos, N. Lattarulo (1997): "Membrane-Based Humidity Control in Microgravity". 27<sup>th</sup> ICES, SAE paper 97-2275.
  27. B. Shaw and L. D. Baver (1939): "Heat conductivity as an index of soil moisture". J. Am. Soc. Agron., vol.(31), pp. 886-889.
  28. S. Shah, A. Hoehn, W.E. Faller, M. Birdsong, M.W. Luttgies (1992): "Characterization of Fluid Distribution Through a Porous Substrate Under Dynamic g Conditions". ISA paper 93-050. Proceedings, 30<sup>th</sup> International ISA Biomedical Sciences Instrumentation Symposium, vol.29, pp. 401-408.
  29. S.L. Steinberg, D.W. Ming, K.E. Henderson, C. Carrier, J.E. Gruener, D.J. Barta, D.L. Henninger (2000): "Wheat Responses to Differences in Water and Nutritional Status between Zeoponic and Hydroponic Growth Systems". J. Agron., vol. 92. In print.
  30. S.L. Steinberg, D.L. Henninger (1997): "Responses of Water Status of Soybean to Changes in Soil Water Potentials Controlled by the Water Pressure in Microporous Tubes". Plant, Cell and Environment, Vol. 20, pp. 1506-1516.
  31. D. Tsao, M.R. Okos, and J.C. Sager (1996): "Controlling the Water Availability from a Ceramic Tube System Subjected to Non-Standard Gravities". Mimeo. 26<sup>th</sup> ICES, SAE-paper 96-1505.
  32. B.D. Wright, W.C. Bausch, W.M. Knott (1988): "A Hydroponic System for Microgravity Plant Experiments". Trans. ASAE, Vol. 31(2), pp. 440-446.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

ALS	Advanced Life Support.
CERES	Capillary Effect Root Environment System.
CO <sub>2</sub>	Carbon Dioxide.
EC	electric conductivity.
H <sub>2</sub> O	Water.
ISS	International Space Station.
KSC	NASA Kennedy Space Center.
MLE	Middeck Locker Equivalent, maximum internal dimensions are D20.320"xW17.337"xH9.969".
MPNE	Microgravity Plant Nutrient Experiment.
NDS	Nutrient Delivery System.
O <sub>2</sub>	Oxygen.
PGBA	Plant Generic BioProcessing Apparatus.
PGC	Plant Growth Chamber.
PGF	Plant Growth Facility.

PGU Plant Growth Unit.  
 pH potential of Hydrogen (alkalinity / acidity).  
 psi Pounds per Square Inch pressure.  
 PTIM Porous Tube Insert Module.  
 PTPNDS Porous Tube Plant Nutrient Delivery System.  
 rH relative humidity.  
 S Siemens =  $\text{Ohm}^{-1}$ .  
 STS Space Transportation System.  
 WCSAR Wisconsin Center for Space Automation and Robotics.

## APPENDIX 1: PGBA WATER REPLENISHMENT

The PGBA plant chamber uses humidity condensate recovery to maintain a constant water content in the root zone. Plants are grown in 'root packs' (Heyenga, 1997). Each pack can be filled with plant-customized soil, agar, or any other desired matrix. The current PGBA packs are 5cm x 5cm x 6.25 cm, but can be customized to a variety of shapes. The packs are made from heat-sealed, gas-permeable polypropylene material. Water can be resupplied from the bottom through a microbial check membrane. In PGBA, the packs are surrounded in the 4 corners by vertical airflow channels. This ensures good gas exchange to the root zone. The polypropylene pack completely contains the water-containing matrix, almost eliminating evaporative losses (1-2 % per day max.).

The packs are typically launched 'wet', filled to the appropriate level with water and nutrients (70-80% saturation). As water is transported from the packs through the plants by evapo-transpiration, it can be condensed from the closed plant chamber atmosphere. The water is then returned through the water distribution system underneath all packs. Each plant / pack can 'suck' water from the distribution 'mat' by capillary action. Assuming a fully sealed chamber, the total mass of water is constant, preventing over-watering. The plants are self-regulating, and no active sensor feed-back is required to maintain the required moisture content. Water with high water demand will be able to take more water 'ad lib'.

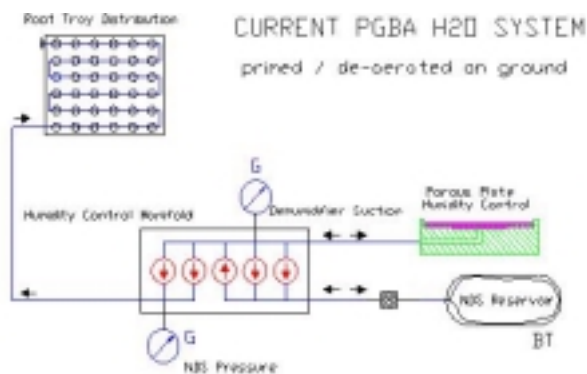


Figure 9. The PGBA Root Zone Hydration System. Replenishable root packs (Heyenga, 1997; Kliss et al., 2000) are placed on a water distribution system (see Figure 1). The water distribution system below the packs is supplied with water from the dehumidification system (bottom picture).

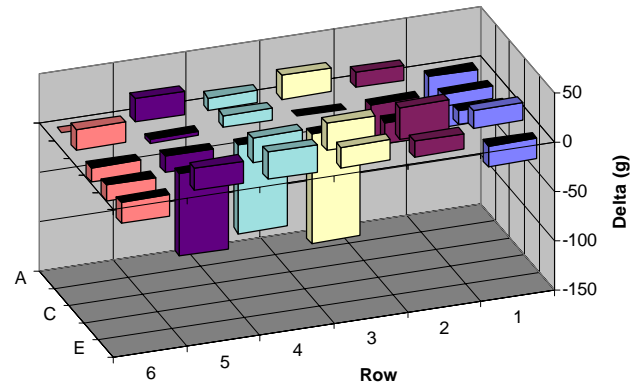


Figure 10. Change of moisture content during 16 day spaceflight of 30 nutrient packs (5x6 array). Large loss of water for 3 packs is from non-replenished packs.

On the last PGBA flight, 6 of the 30 packs were non-replenished, i.e., they had no contact to the water distribution mat. These packs were filled with solidified agar, and radioisotope tracers were added for nutrient uptake studies (Heyenga, 1998). One of the packs grew a single tomato plant, and during the 16 day mission, almost the entire water content of the pack was used up (-100 grams of water out of 150 gram total pack mass – large bar in center of Figure 10). The replenished soil packs maintained their initial moisture content of  $\approx 100$  grams within  $\pm 10\%$  during the entire 16 day mission, despite a daily water-throughput for the pine seedlings of 10-20 grams of water (Figure 10).

## APPENDIX 2 – IMPLEMENTATION OF A POROUS TUBE INSERT MODULE FOR PGBA

The existing PGBA plant growth system (Hoehn et al, 1998) provides atmosphere composition, temperature, humidity and light control. It is designed to use the nutrient packs and return of humidity condensate recovery for root zone moisture maintenance. The PGBA system is fairly modular, and the possibility to test a variety of alternate sub-systems at reduced overall risk was investigated. To accommodate a side-by-side comparison of matrix-based and matrix-free porous-tube nutrient delivery systems (Levine et al., 1998, Wells et al., 2000), only minor modifications to the PGBA are necessary.

The humidity condensate can be used to maintain constant moisture (matrix) or water availability (porous tube). Control of individual tubes or matrix-based delivery systems requires a large array of actuators (pumps, valves) and sensors (pressure, moisture), which are all within the self-contained porous tube insert module (PTIM, Figures 11, 12). The only interfaces to PGBA are multi-drop RS-485 data, power (5 VDC, 12 VDC, 24 VDC), and a humidity condensate return line. PGBA also provides all the heat rejection for power dissipation within PTIM. The use of PGBA as a proven carrier simplifies new design work (only PTIM is new) and reduces overall risk, assuming existing PGBA systems are fully

functional and flight-tested (light, atmosphere, temperature, humidity).

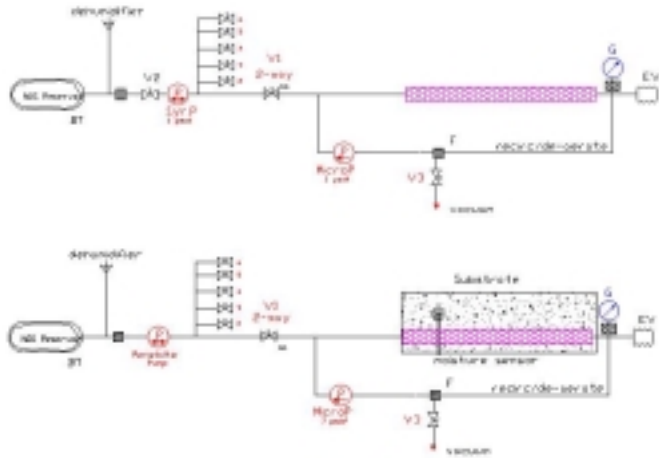


Figure 11. Functional diagram of the 'bare' porous tube (top – no matrix), and a porous tube surrounded by a matrix (bottom). Water can be supplied both from a reservoir (priming) and the dehumidification system. Each tube has provisions for de-aeration (bubble-trap) and water circulation during priming. PTIM is planned to accommodate 6 bare and 3 matrix-surrounded tubes within PGBA.

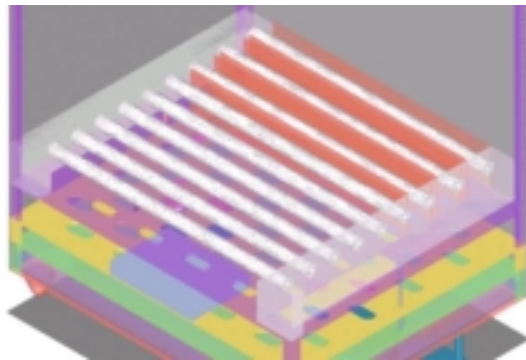


Figure 12. Conceptual view of PTIM within the PGBA plant chamber (6 bare porous tubes, 3 matrix-surrounded tubes). The entire control system including actuators, sensors, command interface, is located below the porous tube. The unique vertical air flow within PGBA is used to ensure proper gas exchange within the root zone area.

### APPENDIX 3. PRESSURE CONTROL IN POROUS TUBE

Both the porous tube nutrient delivery system and the porous membrane humidity control system require accurate control of trans-membrane pressure. Depending on pore size, pressure is controlled to levels in the range of  $\approx -25 \rightarrow -250$  Pa). The sensor needs to be able to measure in a saline / water environment, with electric conductivity in the range of 2 mS/cm.

Calibration of the sensor to maintain a suction pressure of  $-250$  Pa on the tube can be challenging with a tube

diameter of  $\varnothing 2.5$  cm, since, across the tube alone and in a gravity field, a hydrostatic pressure of 250 Pa exists. Depending on sensor location and where the pressure is actually measured, to top of the tube experiences a suction pressure of 250 Pa higher than the bottom. Small calibration errors can yield positive pressures on the bottom of the tube (and subsequent dripping), while the top of the tube is under suction as desired. Once on orbit, the problems associated with hydrostatic pressure will disappear, but parallel ground or centrifuge experiments may be impossible at low suction pressures.

- Hydrostatic Pressure =  $\rho_{H_2O} * g * h$ ,  
typical desired / optimum:  $< 250$  Pa ( $< 1'' H_2O$ )
- Capillary Pressure =  $\frac{2\sigma}{r} \approx 25$  Pa ( $0.1'' H_2O$ ),  
for:  $r = \varnothing 6$  mm I.D., and  $\sigma = 72$  dyne/cm.
- surface tension induced pressure due to air bubbles and wetting  $\approx 0.5'' H_2O$ ,

Air inclusion in the pressure sensor lines can lead to offsets in pressure readings due to surface tension and wetting angles in the same order of magnitude as the desired suction pressure control (250 Pa). Maintaining a suction pressure on the porous tube prevents flooding of the substrate, but also limits the maximum possible flow (Figure 13). The larger the required flow rate to compensate for evapo-transpiration losses, the larger the backpressure through the soil matrix system. The theoretical analysis depicted in Figure 14, for a 5x5 cm, 6.26 cm tall root pack (Figure 9), indicates that, for feed suction pressure of  $\approx -1800$  Pa, adequate flow can no longer be maintained through the pack. If the evapo-transpiration were to exceed the maximum possible flow rates calculated in Figure 13, water would deplete from the root pack.

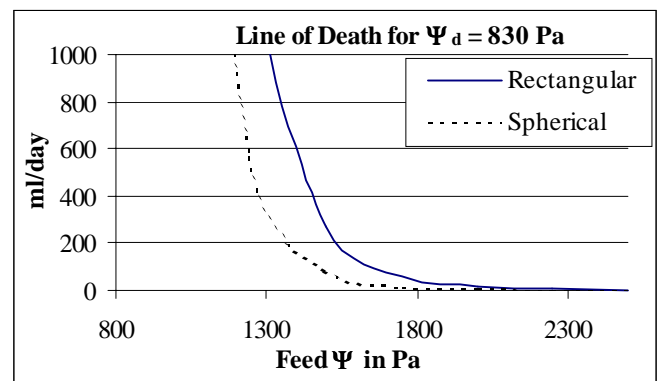


Figure 13. Maximum possible flow rate through a soil matrix as a function of the supply pressure through the bottom of a 5x5 cm root pack, 6.25 cm tall, filled with a soil matrix of  $\Psi_d = -830$  Pa (feed pressure is 'suction').