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Plant Water Management in Microgravity

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The NASA Plant Water Management (PWM) technology demonstrations aboard ISS apply recent advances in microgravity capillary fluidics research towards the mundane yet problematic challenges of simply watering plants in space. Plant growth in a low-g environment is often hampered by inadequate aeration and over-saturation of the root zone. The present effort aims to exploit the passive capillary forces of poorly wetting liquids (i.e., contaminated water) within unique system geometries that effectively replace the role of gravity in providing sufficient aeration and hydration for simulated plants. Several flight demonstrations have been completed on ISS, including soil and hydroponic models in single and parallel channel networks. The results to date demonstrate proof-of-concept, system stability, limits of operation, and more. The implications are discussed in relation to plant growth facilities for further near-term microgravity plant science research as well as for automated food production for long duration human exploration missions.

List of Abbreviations

APH = Advanced Plant Habitat
CCF = Capillary Channel Flow experiment
CSELS = Capillary Structures for Engineering Life Sciences
CFE = Capillary Flow Experiments
LEO = Low Earth Orbit
OpNom = (Flight) Operations Nomenclature
PGU = Plant Growth Unit
PONDS = Passive Nutrient Delivery System
Veggie = Vegetable Production System
FDM = Fused Deposition Modeling
FOV = Field of View
GMT = Greenwich Mean Time
JEM = Japanese Experiment Module
MWA = Maintenance Work Area
PTFE = Polytetrafluporoethylene
PGF = Plant G
PWM = Plant Water Management
TRL = Technology Readiness Level

I. Introduction

PLANT growth in the nearly weightless environment aboard spacecraft is often hampered by inadequate aeration and over-saturation in the root zone. However, food is a critical element for human survival. The continued logistical burden of sending stored food into space to either the International Space Station (ISS) or eventually the Moon or Mars can be remedied with direct food production in the microgravity environment. Scientific experiments such as Veggie[1,2,3], PONDS[4], and others[5,6,7,8] have demonstrated that plant growth in space is feasible but can be improved. To grow plants in any environment, the basic requirements must include water for nutrient transport, biochemical processes, and thermal management. Aeration is also required in the root zone—exhaling carbon dioxide and inhaling oxygen at a minimal but necessary level. The present work seeks to leverage recent demonstrations of capillary fluidics (i.e., CFE[9,10], CCF[11,12,13], CSELS[14,15,16], and others[17,19,20,21,28,]) in microgravity directed toward plant watering as a basis for future plant production systems that operate effectively in a variety of gravity environments.

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The Plant Water Management (PWM) series of simple fast-to-flight technology demonstrations on ISS aim to make passive use of poorly wetting capillary liquids (i.e., nutrient-water solutions) within unique system (i.e., plumbing element) geometries that effectively replace the role of gravity in providing hydration with sufficient aeration for simulated plants.

The PWM project is underway with 2 of 3 proposed flights to ISS completed. The results to date are practical, supporting methods of water management for plant science studies as well as advanced spacecraft food production. Though the focus of the PWM work remains primarily directed toward microgravity hydroponics for automated plant watering methods, some soil-based demonstrations as well as incidental ebb and flow (sometimes referred to as flood and drain) demonstrations are performed and reported. In general, PWM seeks to demonstrate largely passive means for routine, reliable, and stable aerated nutrient-rich water delivery. The point is to establish robust methods for mundane microgravity fluid control such that space plant growth experts can proceed with research and optimization for food production without the nagging uncertainty of the most basic 'should-know-by-now' means of watering plants in space. The challenges of controlling poorly wetting, multi-phase, contaminated liquids in geometrically complex containers in microgravity in the presence of uncertain gravitropic plant responses are acknowledged. Following a brief review of low-g plant watering methods to date, we provide an overview of PWM herein. Further details may be found elsewhere[22,23].

II. Plant Water in Space; 1971 - Present

Nearly all spacecraft platforms have conducted plant research meeting with varied degrees of success[24,25,26,27,28]. Despite many successes, we briefly highlight some of the difficulties encountered due to the various flight watering/nutrient delivery systems. For example, the Soviet Oasis series of experiments aboard Salyut marked the first biological life support flight experiments, flying from 1971 to 1986. The experiments were successful despite the system's fabric ion-exchange root substrate being sensitive to overwatering which was improved in subsequent flights[11]. The Vazon growth system grew bulb-based plants aboard Soyuz 6, 7, and 12, and the Mir space station. The system consisted of planting boxes, a cloth sack filled with ion exchange resin, a water supply system, and an illumination system. Orchids had been chosen as the crop and were launched in bloom, but the mature flowers did not survive. Biogravistat was developed to investigate the effects of microgravity on higher plant shoots on Soyuz 22. It was not initially successful but became so when upgraded by Magnetobiostat imparting magnetic fields and cosmonaut attention. Svetoblok flew on the first progress freighter to supply Salyut 7. The first iteration employed a 1.5% agar-based nutrient delivery system, but other media was used in later versions. The same water delivery system from the prior Oasis experiment was used here. Most plant growth systems failed to support seed-to-seed experimentation for a variety of reason including water/nutrient delivery (Phyton-1, -2, -3)[24].

The ED61/62 experiments flew on Skylab in 1974. Nutrient agar solutions were employed. Out of the 24 seeds sown, only ten germinated. A specially designed automatic seeder implanted three seeds into nutrient agar substrate in each compartment[29].

SVET and SVET-GEMS were plant growth systems flown on the Russian Mir Space Station. Circa 1990, SVET included a water supply system and successfully grew Radishes and Chinese cabbage with samples returned to Earth. The Shuttle-Mir Program was a collaborative effort between Russia and the United States of America and flew the SVET-GEMS experiment which met with limited though improving successes during the 1995-1997 time frame.

NASA's Plant Growth Unit (PGU) and Plant Growth Facility (PGF) were flown on the Space Shuttle between 1982 to 1997. Seedlings were sandwiched between filter paper-like material and an airtight chamber sealed with a gasket below the plant stems. Many of the investigations in these facilities were successful. Astroculture flew on seven STS flights employing a porous tube watering system embedded in a root module containing arcillite and slow-release fertilizer. The Plant Generic Bioprocessing Apparatus (PGBA) flew on six STS flights which included the option to run in either a passive or active water /nutrient delivery mode. The plants were grown in a soil/Agar root matrix system similar to terrestrial models, and the project successfully grew Arabidopsis thaliana, wheat, tomatoes, loblolly pine, spinach, periwinkle, white clover, pepper, sage, and purple coneflower[24].

In 2014, Veggie[1,2,3] was installed on the ISS. Veggie's baseline system utilizes capillary action to wick water passively from a 2-liter reservoir to plant "pillows" that contain an arcillite soil and plant seeds[27,28]. A Nomex® fabric is used as a wick to transfer the water between the reservoir and pillow. A sewn Teflon-coated Kevlar® pouch protects the Nomex wick and reservoir from abrasion and blocks light to prevent microbial growth. At initiation of test Veg-01A, one of the plant pillows failed to wet. Astronauts added water to the plant pillows after 3 of the 5 planted seeds showed no signs of growth. Despite design changes, during tests Veg-01B and Veg-01C, the plant pillows continued to fail to perform the passive capillary water delivery function with water manually added to the plant pillows. The system showed signs of excessive water and condensation. Despite reoccurring plant watering system malfunctions, all three tests produced mature plants that were successfully frozen and returned to ground for investigation.

PONDS[4] is a direct follow-on to Veggie and targets a larger variety of crops. Plant watering is accomplished using a capillary wick to prevent over-wetting of the soil chamber from a separate water reservoir. A Scotch Brite™ sponge pad was used as a breathable barrier for the soil lay-up but proved to be wetting leading to its capillary saturation and resulting in similarly poor performance as Veggie. Also in ISS, the APH[25] facility is a fully enclosed system with an environmentally controlled growth chamber. APH uses an arcillite substrate-based media like Veggie but employs porous tubes buried into the arcillite substrate for forced in-flow delivery rather than wick structures. The root module is primed by filling the plant root zone with water to initiate the experiment. This step initiates seed germination and removes air from the porous tubing and soil media. During initial ISS tests, plant growth data indicated that the priming procedure produced insufficient moisture distribution affecting plant growth and survival.

Under development, SNC's Astro Garden[5,8,31] is the largest and most advanced plant growth system to date, intending to grow a larger volume of food while saving as much space, weight, and power as possible. The eXposed Root On-Orbit Test System (XROOTS) investigation is designed to test hydroponic and aeroponic techniques to grow crop plants without soil, reducing space, and making large scale plant production in space feasible. XROOTS is planned to be integrated with Veggie which provide lighting and air exchange. Cartridges containing seeds will be placed in the XROOTS chambers, and a nutrient solution will be mixed and stored in an XROOTS reservoir.

Current advances in the US will continue and currently include works within the ROSbio program[32]. In 2019, five teams were selected by NASA to further pursue advanced plant growth concepts in orbit. The overall project was entitled "Development of Microgravity Food Production: Plant Watering, Volume Management, and Novel Plant Research on the International Space Station. The teams focus on either (1) edible plant water and nutrient delivery providing sufficiently uniform wetting of the roots, avoid the release of free water, and maintain sufficient aeration and oxygen or (2) provide optimized edible plant spacing/architecture. The former is much like the goal of the PWM technology demonstrations reviewed herein.

Further, in a first extra-terrestrial gravitational environment application, the Chinese National Space Administration recently completed a plant growth experiment on the moon. The Chang'e 4 spacecraft successfully grew two leaves from a cotton plant before dying due to the cold temperature after about two weeks on the lunar surface. Additional crops were sent along with the payload but were not as successful. This was undoubtedly the first step towards growing plants on an alien world. Many similar efforts are sure to follow.[33]

Zabel et al.[24] provide significantly greater detail for the historical contributions of growing plants in space. We are interested here in the success of the water/nutrient delivery systems employed for eventual comparison with the developing methods of novel aeroponic, hydroponic, and ebb and flow approaches. As for nutrient delivery subsystems, the watering methods cited above include water ion exchange resins, cloth ion exchange medium, Cloth sack filled with ion exchange resin, ion exchange resin with water supply, agar based media, foam-wrapped perforated tubing, porous tubes in matrix, soil growth substrate in gas permeable polypropylene bags connected to water supply, perforated tubing wrapped in a wick within a matrix, rock wool fed by integrated water line, passive systems containing varied substrates/materials, manual water and nutrient supply, and many other unspecified and experiment specific methods and hardware. PWM pursues the development and low-g demonstration of advanced plant water delivery methods.

III. The Plant Water Management Experiments

PWM is a series of technology demonstration experiments sent to ISS in pairs that focus on practical liquid delivery methods to representative synthetic plants. Soil, hydroponic, and ebb and flow methods are demonstrated with the lion's share of the attention directed toward hydroponics. Annotated solid models of the flight hardware to date are provided in Figure 1 and will be described in greater detail shortly. The crew conducted experiments are performed in the open cabin of the ISS with TOX-zero nutrient solution ersatz and zero levels of containment—relying solely on capillary stability as a means of control. PWM-Soil (PWM 1) and PWM-Hydroponic (PWM 2) were conceived, specified, fabricated, and on dock in 15 months beginning April 2018. The hardware was launched to ISS on July 25, 2019, but not conducted on ISS until February 2021 due to limited crew availability. PWM-Hydroponics Wedge (PWM 3) and PWM-Hydroponics Cylinder (PWM 4) were similarly prepared and on dock in 14 months beginning August 2019 with launch to ISS occurring in October 2020 and operations on ISS conducted during the March-June 2021 timeframe. Since April 2022, PWM-Hydroponics 5 and 6 are in work with projected hardware delivery, launch, and operations currently planned in 2023. Our generally low-cost fast-to-flight technology demonstration approach promotes the rapid development of sub/system level prototype components that can be quickly incorporated into subsequent hardware to speed the delivery of robust solutions for plant watering in space. Plant water technologies for space missions are not the objective, but the ability to grow plants in space is. Unfortunately, plant watering in microgravity has remained problematic, is indispensable to plant growth, and must be solved simply and as soon as possible.

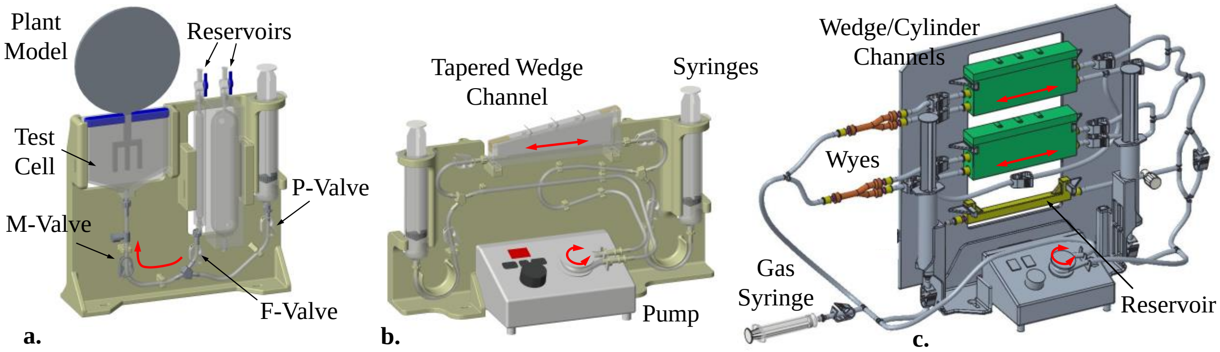

Figure 1: Solid models of PWM hardware. a. PWM 1 Soil with priming (P), fill (F), and main (M) pinch valves indicated (small reservoir connected), b. PWM 2 Hydroponics with tapered wedge channel and bi-directional flow indicated (up to 3 plants not shown), and c. PWM 3 & 4 with generic Wedge (3) and Cylinder channels (4), wyes, reservoir and bi-directional flow indicated (up to 6 plants not shown).

PWM employs a restricted variety of techniques to deliver water using artificial soils, hydroponics, and to a lesser extent, ebb and flow methods that can also benefit from terrestrial verification tests. Container and conduit geometries are rapidly updated via use of 3-D printed parts and synthetic wicking and evapo-transpiring plant models provide an increasingly realistic variety of root/stem/foliage impacts and system-level response. This work is performed under the auspices of NASA Glenn Research Center (GRC) and Kennedy Space Center (KSC) with all contributors seeking to advance spacecraft plant watering technologies toward the point of full automation. An enduring list of PWM engineering objectives includes:

- Demonstrate the combined role of surface tension, wetting, and system geometry to effectively and analogously replace the role of gravity in certain terrestrial soil and hydroponic plant growth systems for applications aboard spacecraft
- Demonstrate hydration and aeration to plant root zone for single and/or multiple plant production chambers
- Demonstrate hydration commensurate with plant growth and evapotranspiration rates
- Demonstrate insensitivity to system excursions, physical perturbations, and g-levels (Moon, Mars, Earth)
- Demonstrate routine and/or turnkey prime, startup, shutdown, drain, long-duration steady states, and transient response
- Demonstrations/considerations for routine plant management functions: i.e., germination, transplant, pruning, harvesting, root clearing, removal, passive fill, and regeneration
- Plans for demonstration of real plants and nutrient solution

Since the focus of this demonstration is on the physical sciences of fluid transfer, no biological components have been used to date. Nonetheless, the simulated plant models employed are made from combinations of wetting rayon felt, nylon string, and a polymeric weave. The simulated plants demonstrate matched wicking uptake and ‘evapo-transpiration rates’ for typical plants. For the PWM-Soil demonstrations, the simple simulated plant geometry is chosen because it may be fully theoretically analyzed from an evapo-visco-capillary flow perspective. For the PWM-Hydroponics demonstrations, the simulated plant root geometries provide elementary geometric obstacles by which to demonstrate flow stability as a function of plant type, plant order, plant number, channel fill level, flow rate, bubble distribution, and more.

IV. PWM 1: Soil

A. Objective

The PWM technology demonstrations primarily focus on hydroponic methods for plant watering in low-g environments. However, one of six PWM hardware items was devoted to substrate ('soil') demonstrations where largely passive capillary methods of liquid delivery to plants could be visualized and measured. Though 'substrate methods' for crop production in space are not necessarily competitive for exploration due to expendable mass penalties, the general ability to efficiently, passively, and consistently water plants in substrates remains a nuisance challenge to plant growth experts conducting low-g plant growth research in LEO.

The PWM-Soil experiments were designed to (1) visually demonstrate passive capillary liquid delivery to simulated plant roots in low-g. The wetting substrate (i.e., arcillite) was suspended in a non-wetting substrate (i.e., Magic Sand) to demonstrate the ability of the wetting substrate to (2) diffusively aerate through direct water-air contact in a manner similar to the 'water table' on Earth. Spontaneous (3) priming, (4) substrate saturation, and (5) foliage wicking, saturation, and effective 'evapo-transpiration' were achieved along with (6) passive reservoir drain and refill operations. These objectives were met by the PWM Soil tests on ISS. The foundation of a theoretical analysis of the evapo-visco-capillary flow throughout the contrived system was also completed through which it was recognized that nearly any 'aerated' passive capillary water delivery profile may be achieved through specific control of media lengths, volumes, pore sizes, and permeabilities. The question is how to know what are the water needs for the particular plant root zone in low-g during the various stages of development? The PWM-Soil demonstrations cannot answer this question.

B. Hardware and Results Overview

The PWM Soil hardware (PWM 1) included a test stand assembly and three different PWM Soil test cells designed to vary the capillary wicking rate to an artificial plant root/stem/foliage model. The OpNom 'Soil' is a misnomer for arcillite granular 'substrate' frequently employed by NASA for studying plant growth in space. Figure 2 provides an image of the test set-up on ISS with the Medium Soil Test Cell along with test cell and plant model details. Three PWM-Soil test cells were examined with Slow, Medium, and Fast control wicks. The hardware was assembled by the crew on the MWA, primed with liquid, and moved to the JEM to an out-of-the way location where time lapse images at 5 minute intervals were collected over an approximately 48 hour period for each of the three test cells. The priming step required the crew to fill the reservoir with our choice for an ersatz nutrient solution—reconstituted Grape and Tropical Fruit Punch Kool-Aid® (sugar) which is readily available onboard ISS. These liquids more closely approximate the surface tension, viscosity, density, and wetting properties of plant nutrient solutions than does clean water. Regarding the priming operations, the 60 mL syringe was filled with the beverage from the crew drink bag and installed on the PWM-Soil backplate as shown in Figure 2a. Using a variety of pinch valve configurations, the liquid was transferred by the crew to the Fluid Reservoir and the soil test cell primed with a final injection from the syringe. Only after capillary inflow was confirmed visually (up to 96 minute wait!) was the hardware transported to the JEM and time lapse photography initiated. Additional reservoir refills by the crew were possible approximately 24 hr into the 48 hr test period. Quantitative data is collected in the form of liquid uptake rates by tracking the reservoir meniscus elevation in time, $h(t)$ in Figure 2a. Qualitative data is collected in the form of approximate advancing liquid fronts through the predominately 2-dimensional Soil Test Cell and Foliage. As shown in Figure 2b-c, the plant models vary 'Control Wick' size which throttles the rate of liquid delivery to the foliage attempting to simulate plants at various stages of development with different uptake requirements: Slow, Medium, and Fast. An accompanying analysis is performed to model the overall transport behavior of the plant models.

The forced priming and passive wicking in-flow to complete saturation of the Foliage is sketched in Figure 3. As liquid passively fills the wetting porous composite structure of the test cell air is first displaced until the plant model is saturated to the stem (Fig. 3d.). Evaporation begins with the onset of Foliage wetting (3d.), Oxygen is free to exchange with the liquid in the Soil Reservoirs (d.-f.), and the flow rate decreases until balance with the evaporation rate from the Foliage (a.-f.). An example of measured transient uptake rate is present in Figure 4a for the Soil Slow test cell. Tuned analytical predictions are presented for comparisons which confirm largely constant infill rates, the curvature of the experimental values attributed to the buildup of sugars in the foliage which reduce evaporation rates, as shown in Figure 4b. This effect may be, but is currently not, included in the accompanying analysis. Similar data was collected for Medium and Fast test cells for comparisons and further model benchmarking.

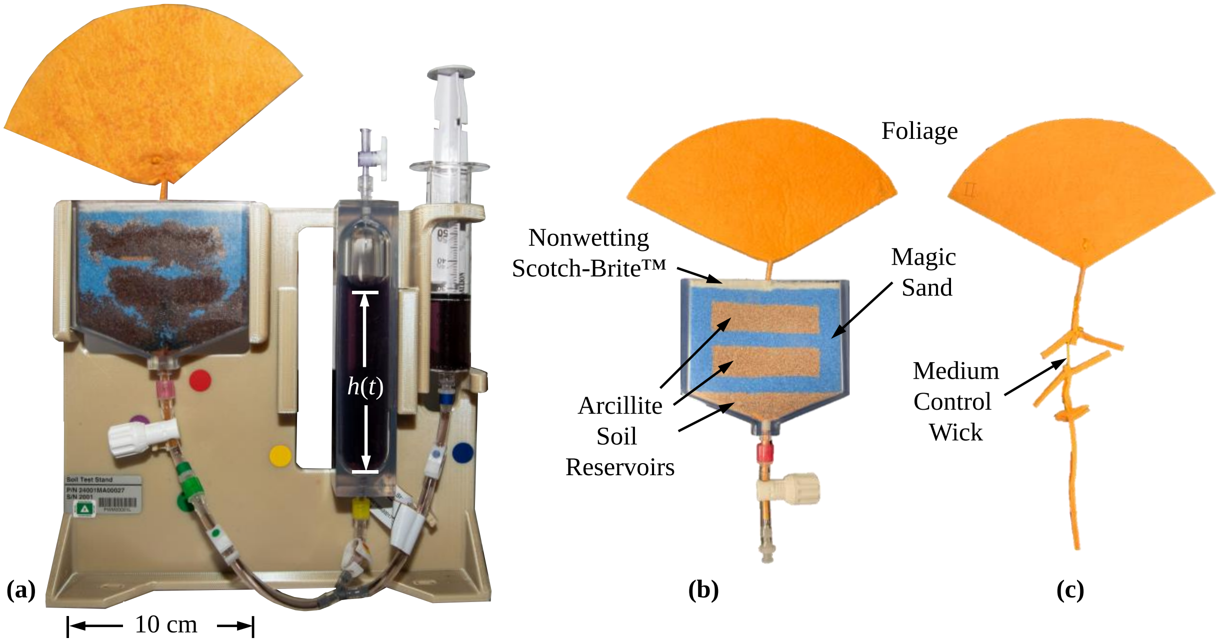

Figure 2: a. Image of PWM-1 Soil Medium in JEM on ISS with large reservoir filled with grape drink (depth of test cell into page is 1 cm). *h*(*t*) identifies meniscus elevation tracked to identify transient plant uptake and 'evapotranspiration rate.' b. Dry Soil test cell and c. structure of Medium synthetic plant model identifying Medium control wick.

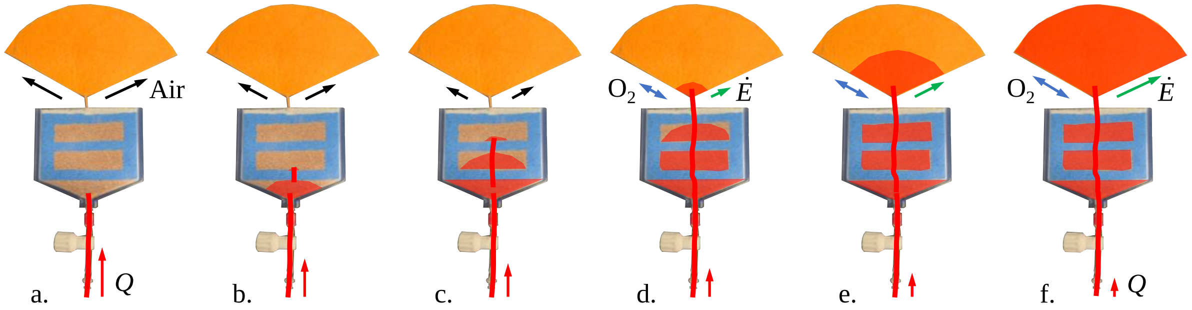

Figure 3. Sketch of PWM-Soil Test Cell a. prime, and wicking into b. Wedge Soil Reservoir, c. c Soil Reservoir 1, d. Soil Reservoir 2, and e. Foliage until complete foliage saturation f. The inlet wicking flow rate *Q* decreases with time. Air is displaced from the test cell in a.-c. as indicated by black arrows. Simulated O_2 exchange and water evaporation $\dot{E}$ from the Foliage are denoted by blue and green arrows, respectively.

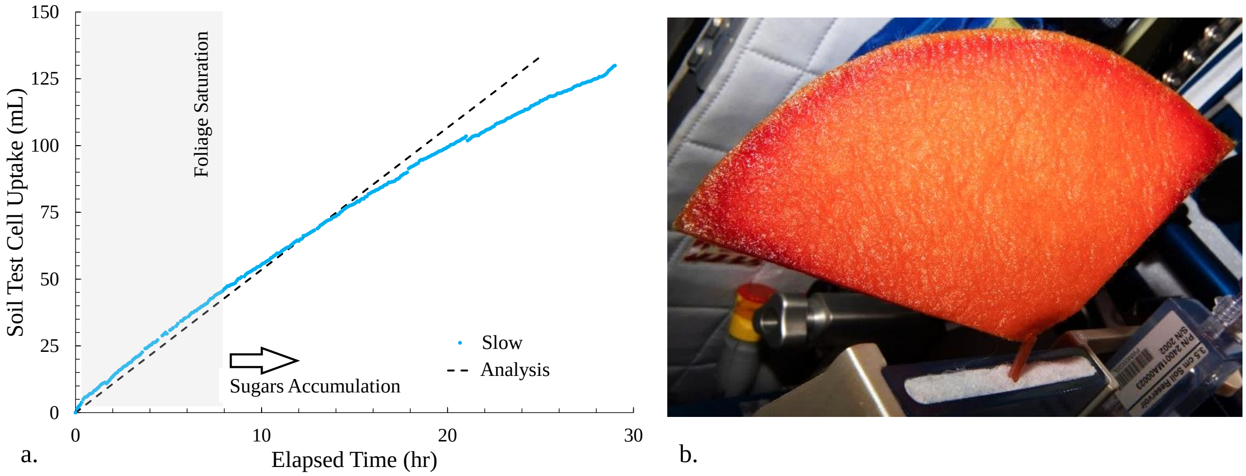

Figure 4. a. Prediction of nearly linear uptake rate for PWM-Soil Slow test cell. Experimental uptake rate decreases after foliage saturation due to reduced evaporation rate caused by increased concentration of sugars in the Foliage—a mechanism not currently addressed by the analysis. b. Visible sugar concentration gradients observed in fully saturated (soaked) foliage after completion of test.

C. Impact and Outlook

The analysis of the synthetic PWM Soil plant models is reported elsewhere[22], where it is found that all of the modeling assumptions are satisfied to a high degree by the PWM Soil hardware and the fidelity of the solutions is tied to the fidelity of the system properties; i.e., porosity, pore sizes, permeabilities, areas, lengths, and the fluid properties of viscosity, surface tension, wetting conditions, and evaporation rate (incl. pressure, temperature, relative humidity, and ambient air flow conditions). The important dependent variables are time-dependent capillary surface advance rate and global liquid flow (uptake) rate. But what does it matter to predict such flows in a static synthetic plant? The plant models are made of any variety of wicks, soil reservoirs, encased wicks (stem), and evaporating foliage. Because all such capillary fluid elements lend to analysis, it seems that nearly any passive capillary fluidic delivery rate can be established by design. Provided such properties can be assigned to real plants at various stages of growth, it seems plausible that a composite wick/soil reservoir system could meet nearly any target watering demands—assuming sufficient O_2 is available in the root zone and that plant roots can pass through short spans of non-wetting media (Magic Sand). An example is sketched in Figure 5 where the combined effects of surface tension, wetting, and geometry replace the role of gravity in re-creating the falling water table phenomena providing increased opportunities for O_2 exchange, nutrient and water uptake, and plant growth. With gleanings from previous substrate plant watering successes[27], the PWM Soil tests on ISS add conclusive visual demonstrations of (1) passive capillary water delivery to (2) 'aerated' soil reservoirs via spontaneous (3) priming, (4) substrate saturation, and (5) foliage wicking, saturation, and effective 'evapo-transpiration' from a single (6) passive reservoir. These flows are well characterized by analysis for the properties of the synthetic plant employed. Can microgravity Plant Scientists exploit this capability?

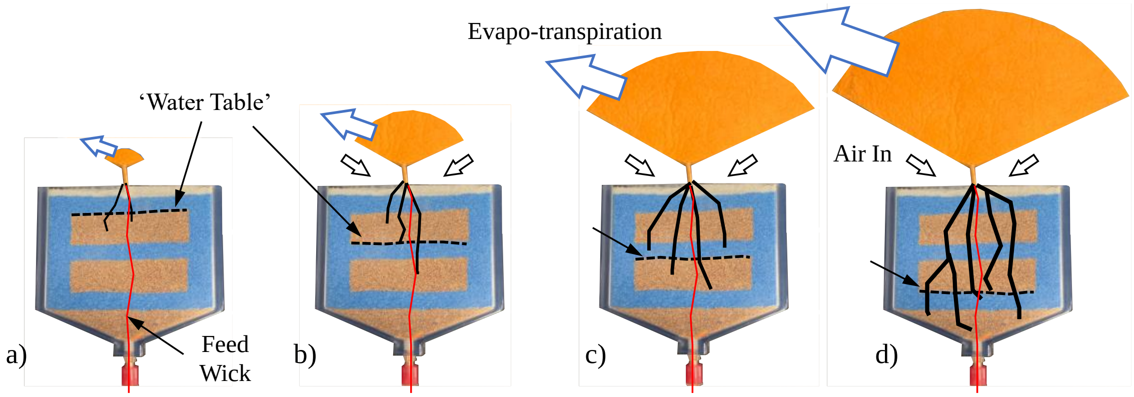

Figure 5. Microgravity example of how a growing plant within a PWM-Soil-like planter might establish an Earth-like falling water table phenomena as the roots reach deeper and water uptake requirements increase.

V. Hydroponics Investigations (PWM 2, 3, and 4)

A. Objective

The primary objective of PWM is to demonstrate stable water delivery in low-g for advanced hydroponic plant production. The open wedge channel serves as an ideal geometry for which to accomplish this task due to its highly stable, passive, visco-inertial-capillary flow characteristic along the channel. The wedge geometry provides a passive pumping function along the channel due to a capillary pressure gradient. It also provides for increased stability with decreasing fill level and a natural tendency to exude bubbles to the free surface where they can coalesce and leave the flow. Such passive bubble separating characteristics are desirable helpful for both purposeful and inadvertent bubble management. Solid models of PWM hardware to demonstrate this approach to plant watering were presented in Figure 1b. and c. Significant low-g open wedge channel research has been established via drop tower[35], aircraft[36,37], and ISS research (CFE[9,10], CCF[11,12,13], CSELS Science[14,15,16]). Flight images for PWM-Hydroponic (PWM 2) are provided in Figure 6, and for PWM-Hydroponics Wedge (PWM 3) and Cylinder (PWM 4) in Figure 7.

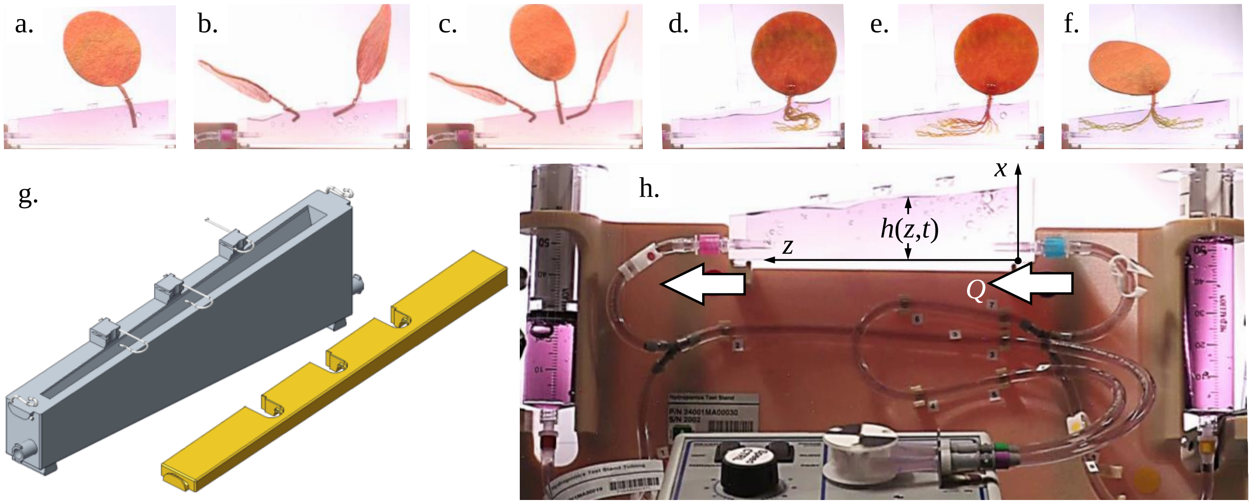

Figure 6. PWM 2 Hydroponic hardware on ISS with a.-f. plant models in g. tapered wedge channel with flow of Grape Kool-Aid™ right to left identified in h. Simple single, double, and triple rayon felt tap root plant models are shown in a.-c. with composite nylon-rayon felt model shown in d.-f.

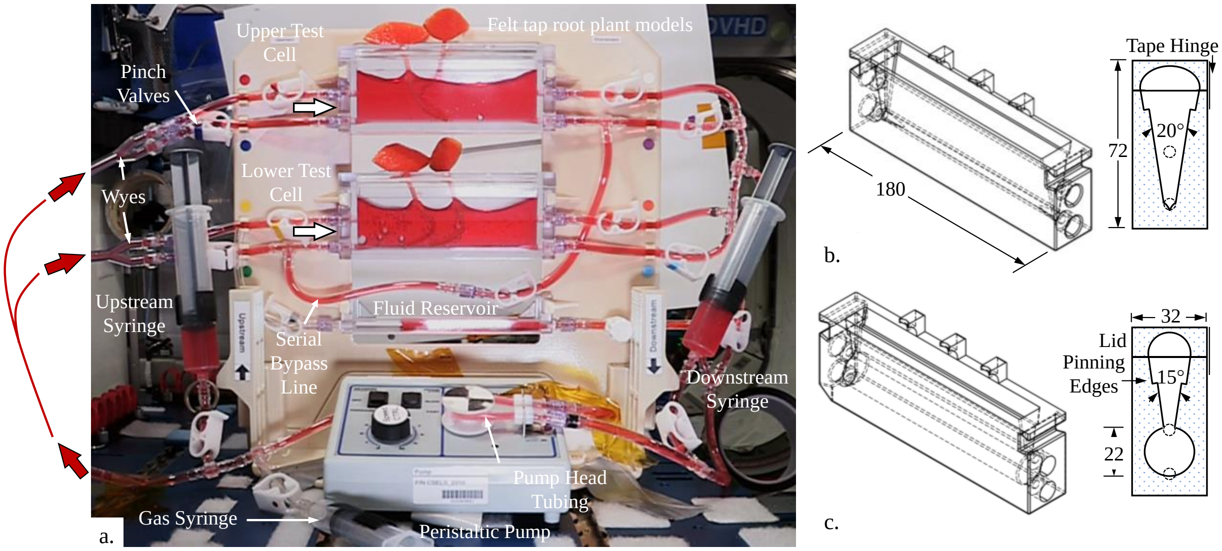

Figure 7. a Flight image of PWM-Hydroponics with parallel channel flow for b. -3 Wedge and c. -4 Cylinder open flow channels. Wedge channel test is shown in a. with flow direction indicated (dim. in mm).

B. Hardware and Results Overview

PWM 2 employs a single tapered open wedge channel, the taper providing a passive reorientation mechanism toward the narrow end of the channel in the event of a destabilization of the desired free surface configuration for flow right to left in Figure 6. The flow is reversible and inertial-capillary flows demonstrated stable set-points in the counter flow direction (left to right in Figure 6). Dozens of stable steady states and limits of operation varying flow rate and fill level with and without simple plant models installed were demonstrated. Practical mundane prime, fill, start-up, flow, shut-down, and re-start, etc. were also demonstrated during the approximately 7 hr of ISS run time. To date the PWM 2 results have not been reported in detail, being overshadowed by the wealth of data provided by PWM 3 and 4 collected on ISS only one month after that of PWM 2.

PWM 3 and 4 employed the same hardware shown in Figure 1c and 7a, and swapped out open channel test cells Wedge and Cylinder. The PWM-Hydroponics Cylinder channels made an attempt to consider hybrid channels making use of wedge and cylindrical root accommodating volumes. Two pairs of channels were employed for operations in parallel and serial modes, with an emphasis on the limits of parallel channel flow stability. Two inlet/exit ports provided ample variety for upstream bubble separations using wye- and two other capillary fluidic bubble separating devices reported elesewhere[23,38,39]. Plant types employed are pictured in Figure 8. We list the salient accomplishments of the PWM-Hydroponics 3 and 4 tests below:

- 1, 2, and 4 plant single and parallel flow configurations with single tap, nylon, and composite root models (Large, Medium, and Small) with limits of stability
- All inlet permutations, > 42 hr nearly continuous operation, and > 400 steady states/test points achieved
- Maximum flow rates Q achieved in all configurations ($0.5 < Q < 7$ ml/s)
- Passive creation and delivery of wide dispersions of aerating bubbles: bubble interactions with bubbles, flow channel free surface, root structure, and no-moving-parts steady venturi aeration
- Passive aerating bubble separations and limits of performance as functions of bubble size, distribution, and Q
- > 99.5% separation regimes established for two bubble diverter designs (swappable for wye fittings in Figure 7a)
- Demonstrations of liquid depth effects, passive reservoir make-up water, serial operation, flows against capillary gradient, high inertial flow stability, mundane ebb and flow, and more
- Practical clean plant model installation, channel fill, drain, and plant removal in the ISS open cabin

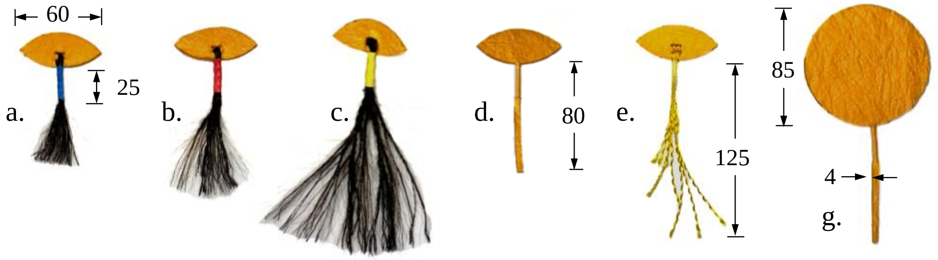

Figure 8. PWM 3 and 4 Hydroponics plant model types: a.-c. short, medium, and long weave, d. small tap root rayon felt, e. nylon-rayon felt composite, and g. large tap root felt plant models (dim. in mm).

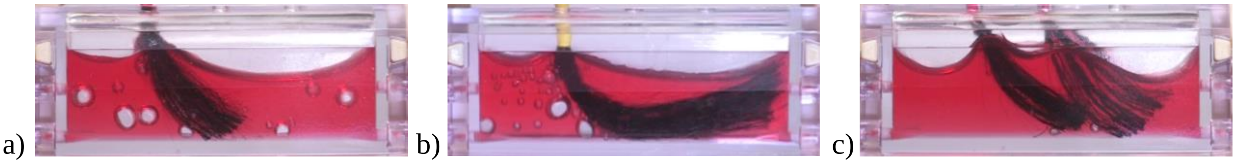

Figure 9. Dynamic interface configurations in PWM-Hydroponics Wedge channels for a. single small, b. single large, and c. double small weave plant root models. Purposeful or inadvertent bubble eventually merge and are forced to the free surface where they coalesce and leave the flow. C) is a long-time largely bubble-free steady flow condition.

C. Impact and Outlook

The PWM 3 and 4 hydroponics data has been logged for archive in NASA's Physical Sciences Informatics database, https://www.nasa.gov/PSI, with hyperlinks to source HD video data as well as over 430 individual clips with reduced data for fill levels, flow rates, crew member, GMT, etc. The archive will be made publicly available in 2022.

A developing summary of the findings helpful for the further engineering development, design, and deployment of such low-g poorly wetting hydroponics systems is taking shape and suggested below:

- Slow visco-capillary parallel flows are stable for a wide range of fill levels
- Inertial-capillary partially pinned parallel channel flows are stable for high fill levels below a critical flow rate
- Inertial-capillary parallel channel flows drift for low unpinned fill levels at elevated flow rates
- Inertial-capillary parallel channel flows are easily balanced by flow control/resistance adjustments and/or increased fill level, reduced flow rate, or robust pinning edges
- Successful system prime is natural due to the passive bubble separating characteristics of the Wedge channel geometry—the Cylinder channel geometry is not as effective in this regard
- Specific flow behavior depends on dynamic and static bubble distribution, inlet/outlet conditions, inlet/outlet type, fill level, flow rate, and root geometry which changes with number of plants, size, and shape
- Current channel sizes are stable to significant crew perturbations (~ $10^{-2}g_o$)

The hydroponics system demonstrated works in all gravitational environments provided the g-vector is downward. Though a significant foundation is available[23] from which to design functional hydroponic plant watering equipment for spacecraft, a significant shortfall is the lack of demonstration with real plants. This is a goal of the PWM 5 and 6 experiments planned for 2023.

VI. Future Plans

Designs for PWM 5 and 6 are underway with expectations of launch to and operations aboard the ISS in 2023. The demonstrations currently envision further integrated system development for low-g serial and parallel dual-mode hydroponics and ebb and flow plant watering methods: 100 hr operations with 4 to 8 channels, turnkey prime and start-up, complex realistic 3-D printed simulated plant root models, active/passive flow control, passive aeration, passive bubble diversion and separation, passive capillary reservoir make-up water, non-wetting/non fouling components, and quantified flow rates, fill levels, fluid distribution, stability, and fluid/plant wetting properties. Special considerations are being made to pursue permission for use of true nutrient solution such as https://www.aerogarden.com/liquid-plant-food-nutrients-1-liter.html for greater than 48 hr continuous operation (current NASA experiment time limit due to microbial growth concerns) with a base plate compatible with, for example, APH or Veggie such that demonstrations with real plants from germination to maturity can be conducted at crew/program discretion. The requirements for the PWM 5 and 6 hardware are expected to be fully defined by mid-2022.

VII. Conclusion

The PWM technology demonstrations on ISS have pushed the readiness of microgravity hydroponic plant watering systems to ~ TRL 7. The approach is now ready for further development with real plants aboard spacecraft. The recent progress highlighted herein is a result of demonstrated stable open flow channel geometries that passively separate bubbles. This is not a challenge on Earth where liquids simply flow along the bottom of such channels while bubbles simply rise and leave the flow due to gravity. The parallel and serial channel arrangements of PWM-Hydroponics mimic the performance of terrestrial systems by replacing the role of gravity with the combined roles of surface tension, wetting, and conduit geometry. The liquid is stably held within the channels while bubbles passively exuded from them by these same combined capillary effects. An essentially passive fluid delivery system is thus achieved with simplicity as well as reliability on par with residential if not commercial hydroponic gardening and farming systems on Earth. Therefore, the design of this hydroponics system can be scaled for equivalent operation in either terrestrial, lunar, or microgravity scenarios where different g-levels drive the stability of the wetted interface of the system, thus making it a truly omni-gravitational hydroponics experiment.[38,39]

In the process of the PWM-Hydroponics development efforts to date, as clearly identified by NASA[40] and through guidance of the National Research Council[41,42], we confirm that poorly wetting liquid-gas two-phase flows, regime transitions, and separations in complex geometries in microgravity are the fundamental as well as principle applied challenges for watering plants aboard spacecraft. We expect this to be true for all watering methods including hydroponics, ebb and flow, aeroponics, and others. We expect that scale-up of any such method when applied to long duration plant water delivery aboard spacecraft will ultimately produce a plumbing system riddled with bubbles and ullages[31], requiring complex active, if not passive, microgravity phase separation unit operations. However, a bubble need not be treated as a nuisance. On the contrary, steady streams of bubbles provide vital oxygenation as commonly exploited in terrestrial systems from trickling hydroponic plant growth chambers to aquaponic fish tanks. The PWM technology demonstrations have shown[39] that streams of aerating bubbles may be passively produced and passively separated providing fully oxygenated nutrient solution to the root zone, in much the same manner as achieved on

Earth. It is the other-worldly response of the plants in such microgravity systems that remains to be observed and addressed. PWM-Hydroponics 5 and 6 seek to address this shortfall with expectations approaching TRL 8 in 2023.

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