National Aeronautics and Space Administration

Plant Water Management (PWM)

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PLANT WATER MANAGEMENT
PORTLAND STATE UNIVERSITY
PWM
ZIN TECHNOLOGIES
NASA GRC
NASA KSC

ASGSR 2019

Overview

- Plant Water Management Team
- Science Background
- Experiment Hardware
- Analysis of System
- Future Plans

PWM Team Contacts

SCIENCE

Name	Role	Affiliation	Email
Dr. Mark Weislogel	Principal Investigator	Portland State University	mmw@cecs.pdx.edu
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MANAGEMENT

Name	Role	Affiliation	Email
Kelly Bailey	Project Manager	NASA	kelly.a.bailey@nasa.gov
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NASA's Plant Water Management Challenges

- **Plant watering is complicated by the absence of gravity:**
  - aeration (gas/fluid interactions)
  - diffusion of nutrient solution
  - root growth

- **The specific needs at any point in time can vary based on the life cycle of the plant, from germination though harvest.**

- **Prior experiments have seen unexpected water migration to the due to surface tension forces, and poor aeration of the soil.**

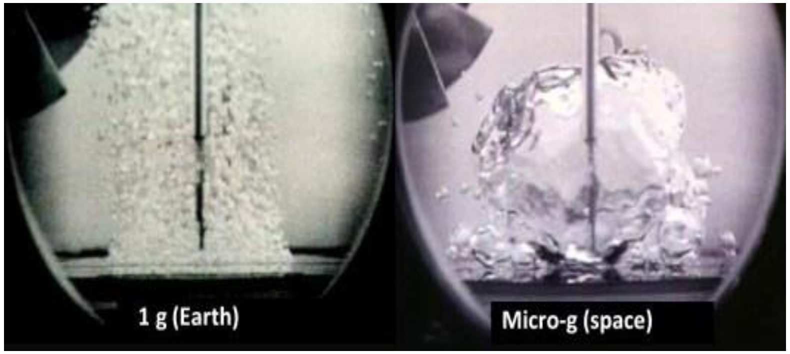
- **We are looking for simple, robust methods for advanced systems.**

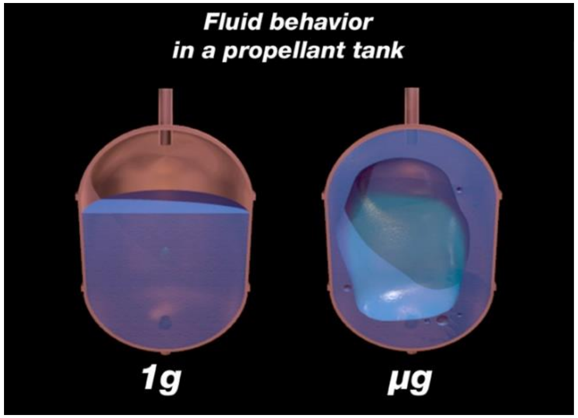
Significance of Fluids Management

Virtually all major systems involve fluids management

(or mis-management)

Physical sciences research on the ISS provides the knowledge base for designing systems, ISS provides a platform to validate technologies for inclusion in flagship missions.





PWM Science Objectives

- **Demonstrate ability to provide hydration and aeration to plant root zone throughout the plant life cycle from germination through harvest**
- **Demonstrate ability to provide hydration and aeration to plant root zone for single plant chambers or multiple plant production chambers**
- **Demonstrate ability to control liquid inventory via capillary forces within either in an open container and/or a container with semi-permeable covers**
- **Demonstrate an ability to provide sufficient hydration commensurate with plant growth and evapotranspiration rates**
- **Demonstrate ability to provide hydration and aeration to plant root zone in a geometry that can be utilized in both a normal and microgravity environment**
- **Demonstrate routine priming, startup, shutdown, steady and transient operation**

PWM is a *Technology Demonstration* of recent advances in micro-g capillary fluidics research applied to plant growth systems

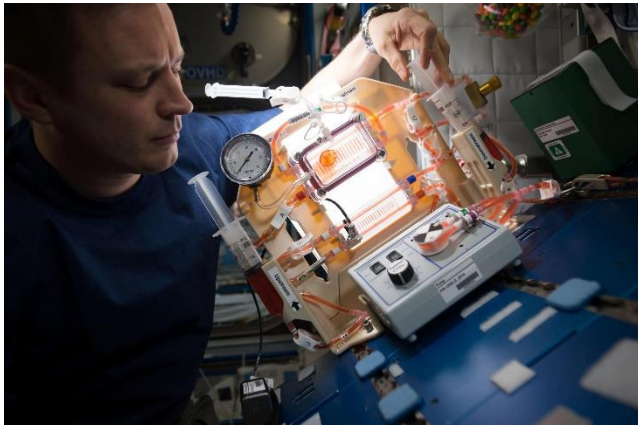
PWM Approach

Watering Schemes and Factors:

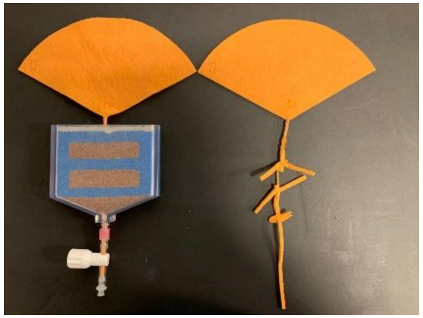
1. Soil
2. Hydroponics
3. Root Accommodation Zone
4. Parallel Hydroponic Trays
5. Capillary Based Degassing and Liquid Aeration
6. Humidified Root Zone

Test Facility:

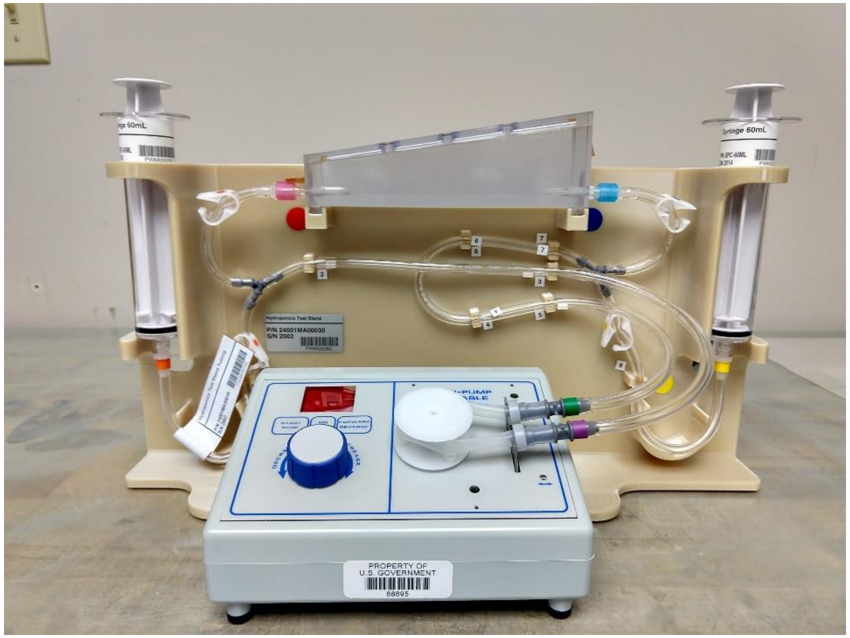
- Maintenance Work Area (MWA) on ISS
- Crew Involvement
    - Setup
    - Priming
    - Adjusting Flow Rates
    - Dispose of hardware after use
- Data Analysis based on Downlinked Images

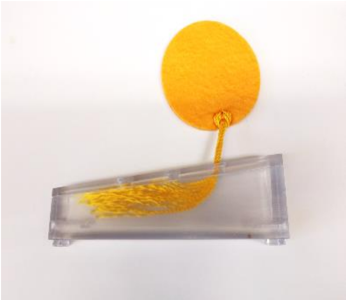


PWM 1 (Soil)



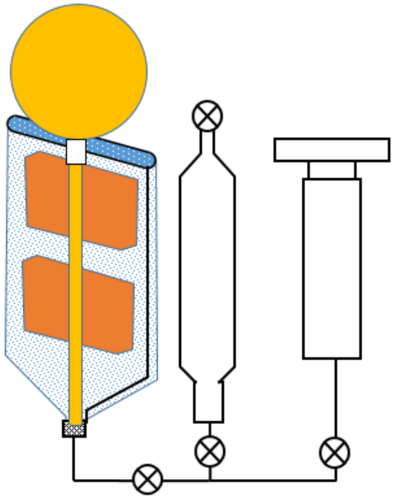
PWM 2 (Hydroponics)



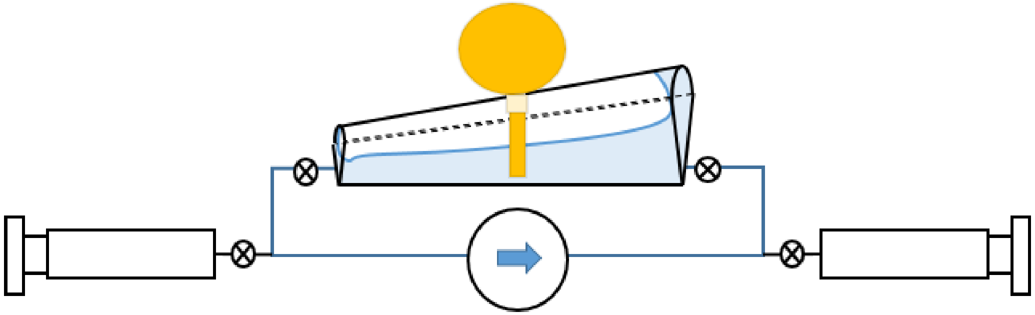


PWM Hardware Flow Loops

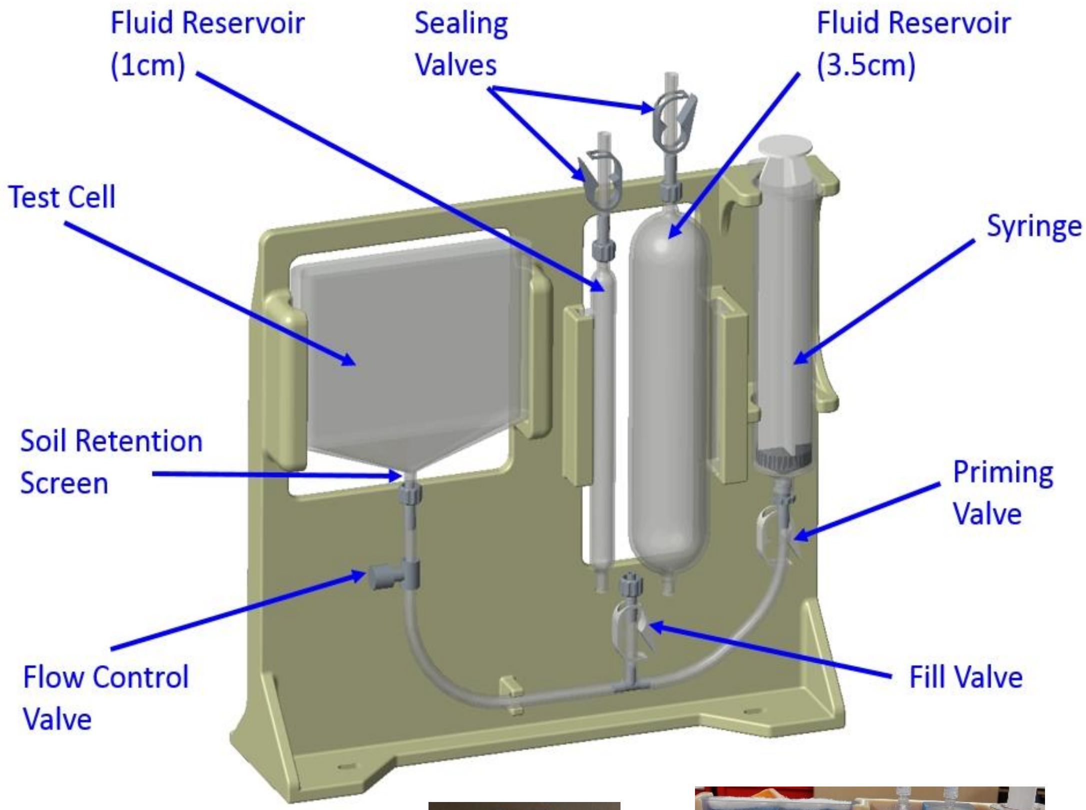
PWM Soil

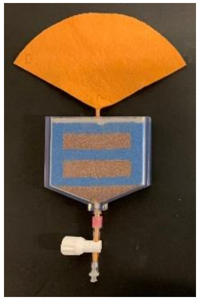


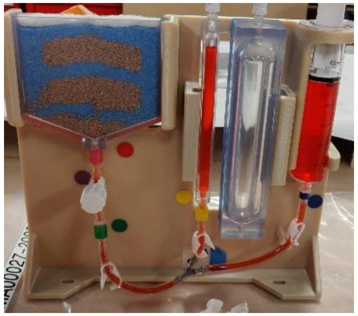
PWM Hydroponics



PWM-01: Soil

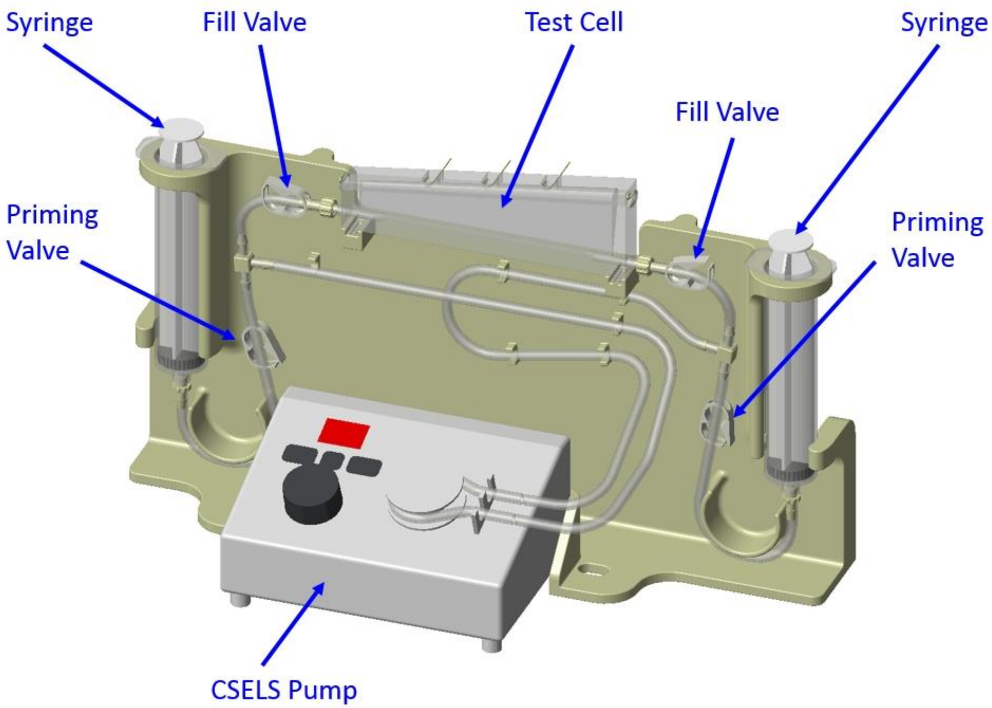


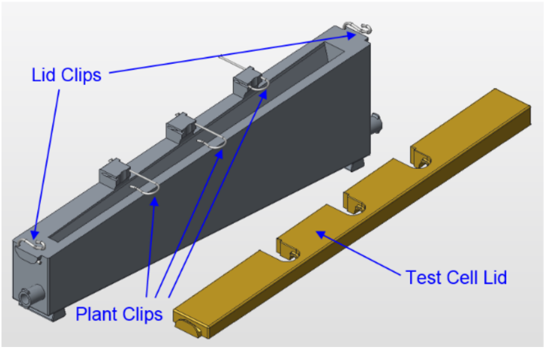




Component	Material
Test Stand	Ultem (3D Printed SLA)
Test Cell	Accura 60 (3D Printed SLA)
Test Fluid	ISS potable water mixed with Kool Aid® Tropical Punch (from the ISS On-orbit food pantry)
Plant Simulant	Rayon Felt/Nylon String Composite
Soil Simulant	Arcilite / Magic Sand
Soil Retention Screen	Rayon Felt Plug
Fluid Reservoirs	Accura 60 (3D Printed SLA)
Syringe	COTS Plastic, Luer
Fluid Lines	COTS Tygon
Fittings and Valves	COTS Plastic, Noncontact Pinch Style, Luer

PWM-02: Hydroponics





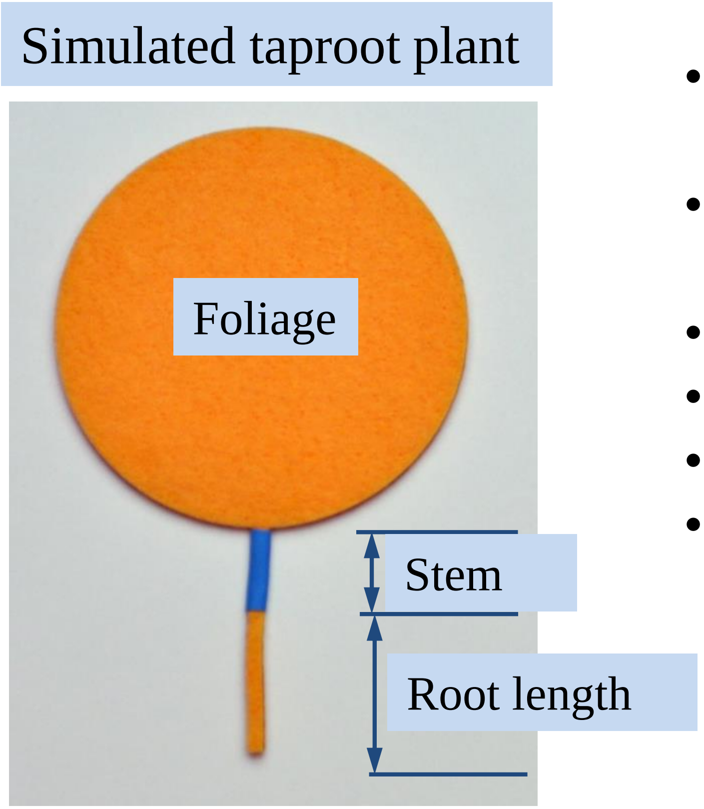
Component	Material
Test Stand	Ultem (3D Printed SLA)
Test Cell and Lid	Accura 60 (3D Printed SLA)
Lid Clips	Stainless Steel
Plant Clips	Stainless Steel
Test Fluid	ISS potable water mixed with Kool Aid® Tropical Punch (from the ISS On-orbit food pantry)
Plant Simulants	Rayon Felt / Nylon String Composite
Pump	Peristaltic, Positive Displacement, from CSELS Experiment
Syringes	COTS Plastic, Luer
Fluid Lines	COTS Tygon
Fittings and Valves	COTS Plastic, Noncontact Pinch Style, Luer

Fluid/Soil Properties

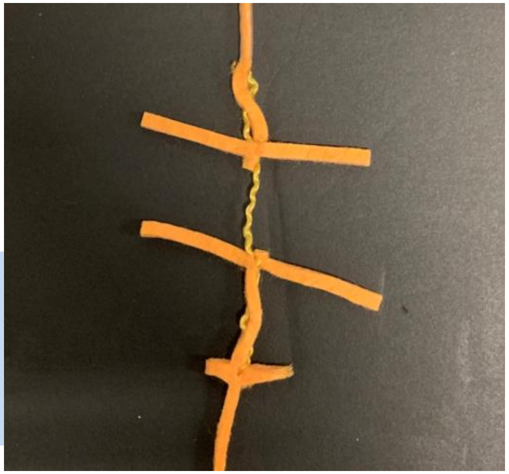
- **PWM Soil & Hydroponics Test Fluid**
  - Water mixed with “Tropical Punch” red drink mix from ISS pantry
  - Sucralose sweetener included in drink mix
  - Kinematic viscosity: 1 CS
  - Benefits:
    - Flow visualization
    - Poorly wetting fluid (sweetened water)
    - Mixed solution similar to plant nutrient mix
    - Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups

- **PWM Soil Media**
  - Arcillite
    - Commonly used as soil basis for prior NASA plant growth systems such as VEGGIE, PONDS, APH, etc.
    - Calcinated clay particles, highly wetting when dry, clumps when saturated
  - Magic Sand
    - Nonwetting hydrophobic media
    - Breathable soil in contrast to the arcillite

PWM Plant Simulants



- 4mm thick, uncompressed & washed rayon felt foliage, stem, and taproot
- Uncompressed nylon string as secondary wick for fibrous roots and germination stage
- Max “plant” volume (foliage/stem/roots): 53mL
- Infill wicking rate: 7.7 mL/hr – 155mL/hr
- Evaporation Rate 2 mL/hr – 7.7 mL/hr
- Characteristics based on "Outredgeous" red romaine lettuce plant from germination to harvest

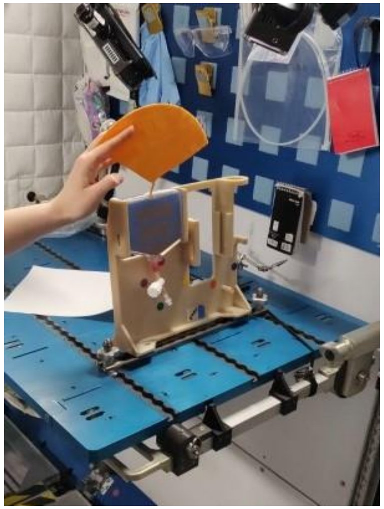


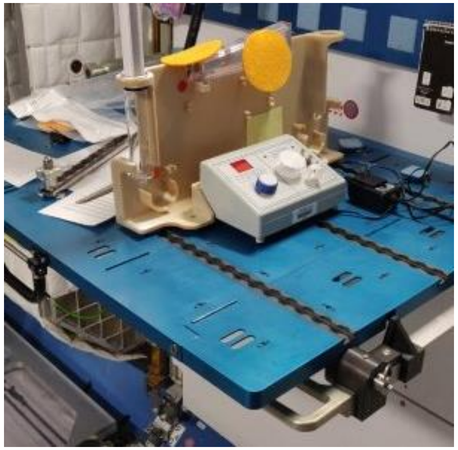
PWM Operational Overview

1. Collect hardware (including PWM kit, ISS-provided lighting, cameras, potable water, drink mix, and CSELS pump).
2. Assemble hardware on MWA. Start video recording.
3. Slowly prime the system with the test fluid and start the pump (hydroponics only).
4. Take images of the pump rate, shape of fluid in the test cell, and motion of plant roots, porous wicking gradient, saturation gradient, and bubble formation/occlusion at variable flow rates.
5. Drain the system and dispose of the hardware.
6. Downlink videos and still images for analysis.

Approximately 3 hours of crew time per experiment (3 soil, 1 hydroponics).

Soil demonstrations can be left overnight (untended) due to slower wicking rate.

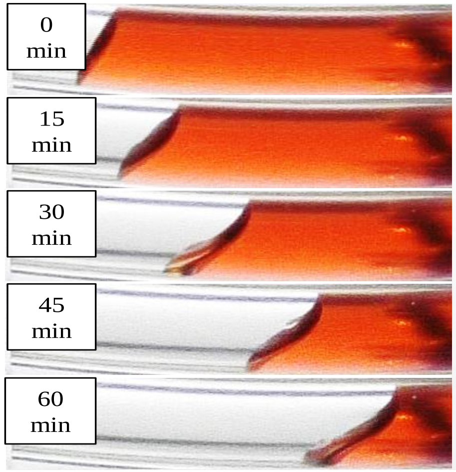


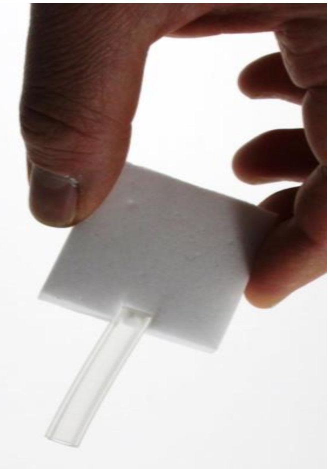


Importance and Reason for ISS

Duration of microgravity test conditions:

- **System prime and steady-state stability in complex micro-g geometry**
- **Allows establishment of steady pumped flow with evaporation on timescales that cannot be achieved in drop towers or aircraft.**
- **Crew tended experiment**
  - Extra science potential for g-jitter stability response, bubble formation/occlusion/recovery

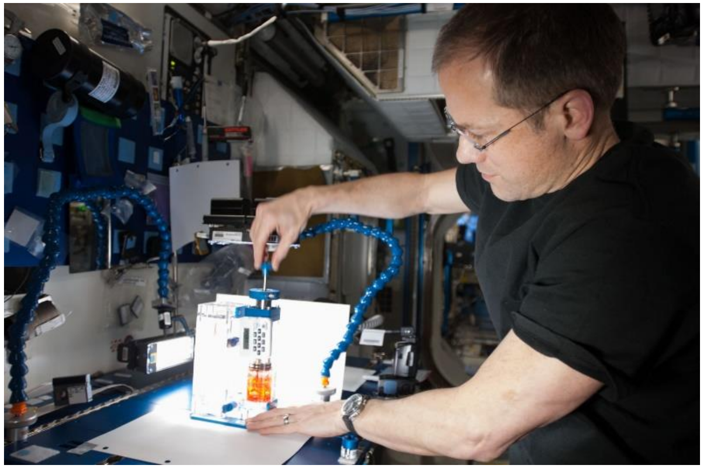




CSELS Experiment example of long-duration evaporation rate testing

Requirement Rationale

- PWM is conceptually similar to Capillary Flow Experiments (CFE) and CSELS (Capillary Structures for Exploration Life Support), both led by the same PI
- PWM is a further demonstration of capillary methods for applied fluid control, potential path forward is known
- Reutilizing similar or identical hardware, flight-cert. COTS, task listable, same players from original experiments
- Both of these experiments yielded dozens of hours of extra crew time for extended science due to their simple nature



Theoretical Analysis – Porosity

- Water Content Θ_w and Air Content Θ_a

$$\Theta_w = {}^{V_w}/_{V_{total}} \qquad \Theta_a = {}^{V_a}/_{V_{total}}$$

- Porosity n

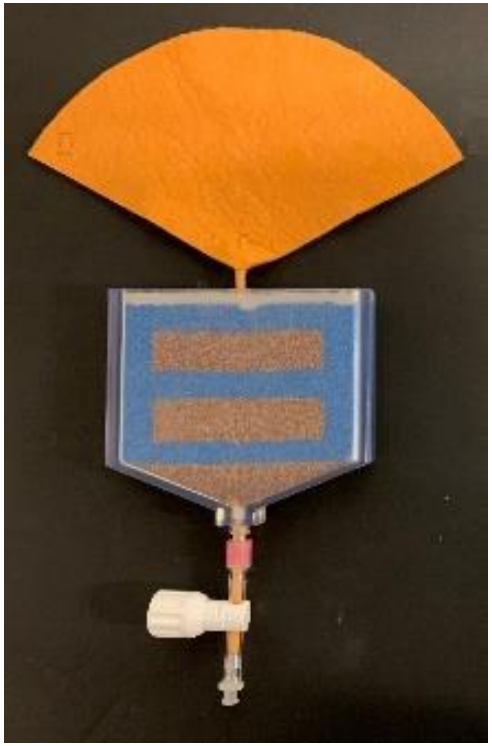
$$n = {}^{V_w + V_a}/_{V_{total}}$$

- For reference:

$$\Theta_{w,arcillite} \approx 0.50 \qquad \Theta_{w,magic\ sand} \approx 0$$

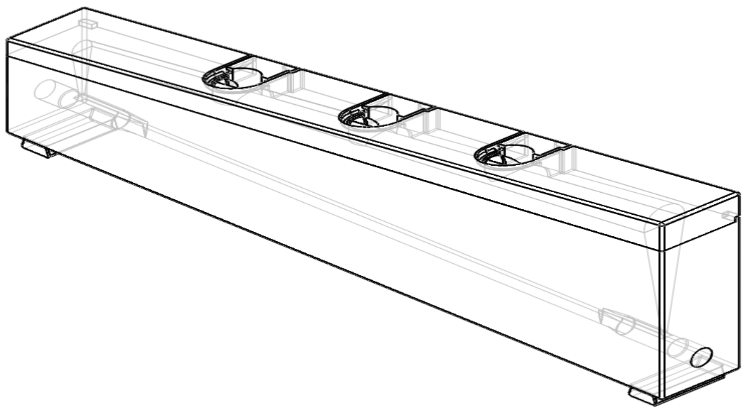
$$\Theta_{a,arcillite} \approx 0.15 \qquad \Theta_{a,magic\ sand} \approx 0.66$$

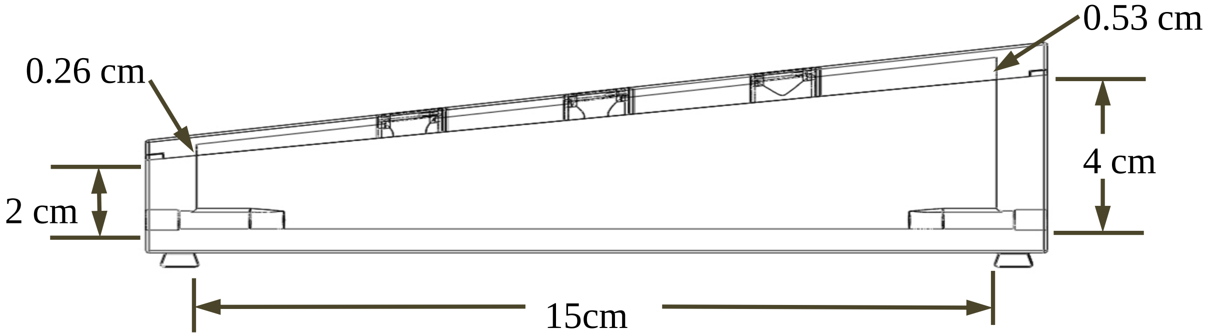
$$n_{arcillite} \approx 0.65 \qquad n_{magic\ sand} \approx 0.66$$

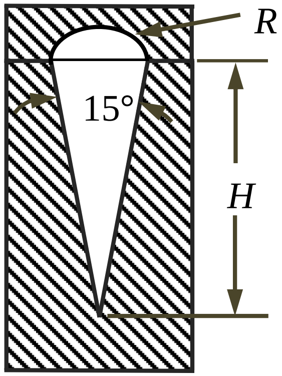


Theoretical Analysis

- Continuing to work on characterizing soil system…
- But hydroponics plant growth is the clear path forward for low-g systems!







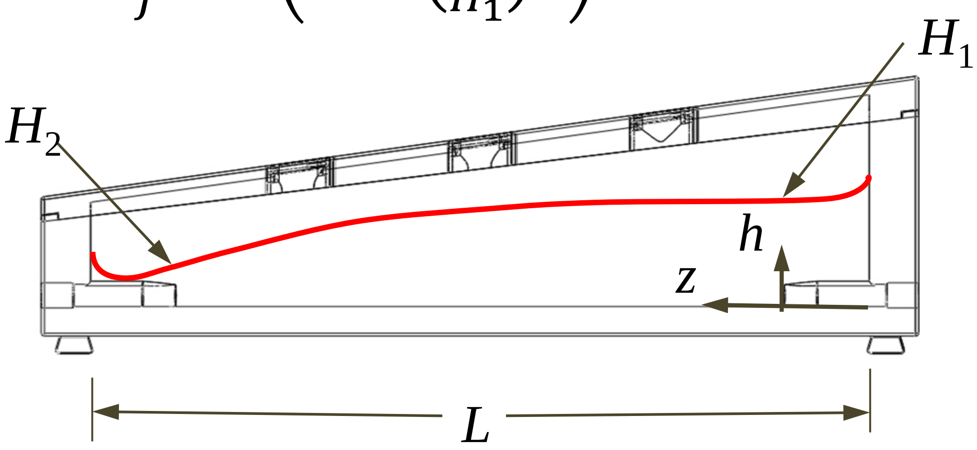
Hydroponics Analysis

- **For known H_1 and H_2 the free surface profile can be determined by**

$$h = H_i\left(1-\left(1-\left(\frac{H_2}{H_1}\right)^3\right)\frac{z}{L}\right)^{1/3}$$

- **Flow Rate**

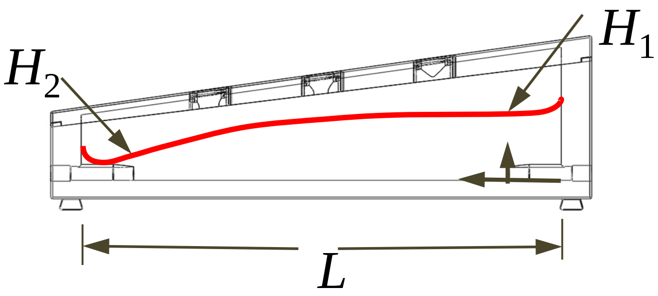
$$Q = \frac{\sigma}{\mu}\frac{F_A H_i^3}{3L}\frac{F_i\,(\sin\alpha)^2}{f}\left(1-\left(\frac{H_2}{H_1}\right)^3\right)$$



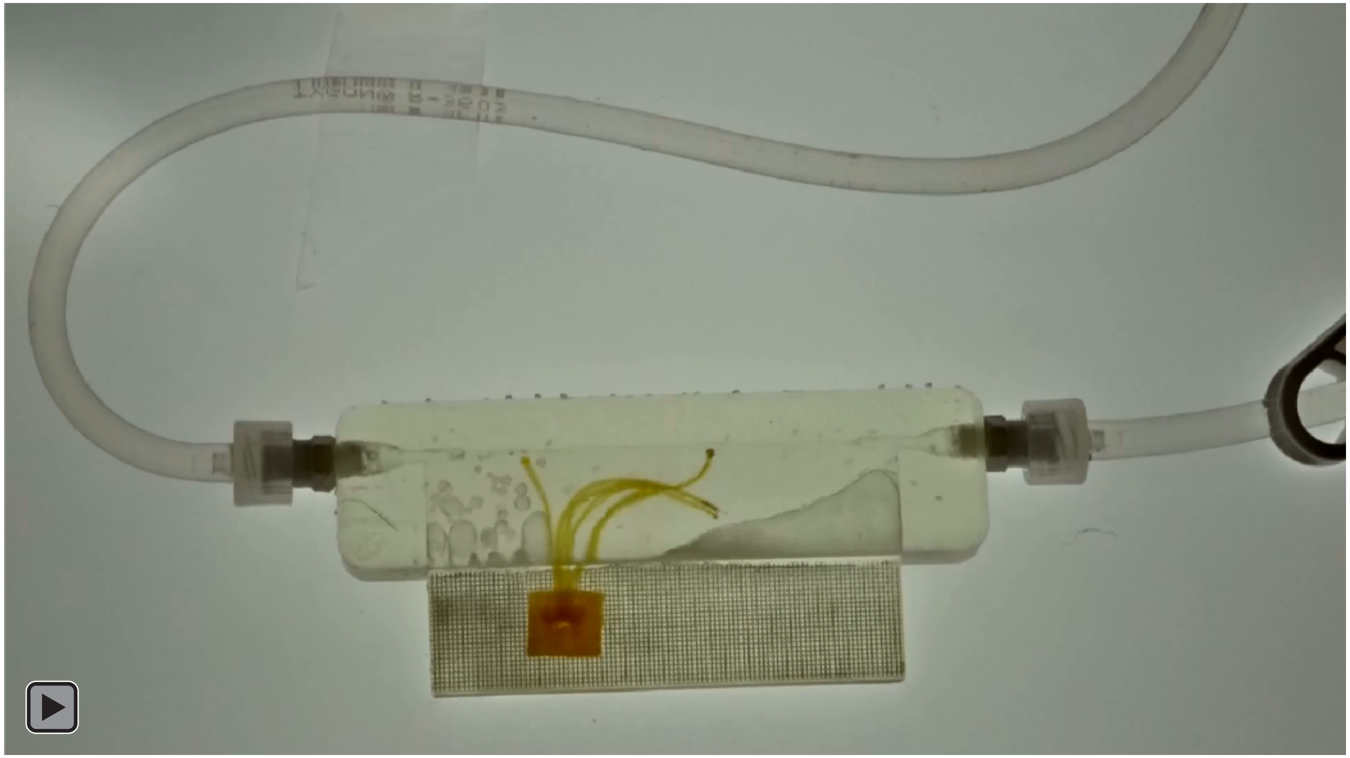
Hydroponics Analysis

- **Governing Equations based on ISS Capillary Corner Flow Experiment (~2013)**
- **Use Concus-Finn critical contact angle to control liquid position**
- **This can be expanded for parallel channels**

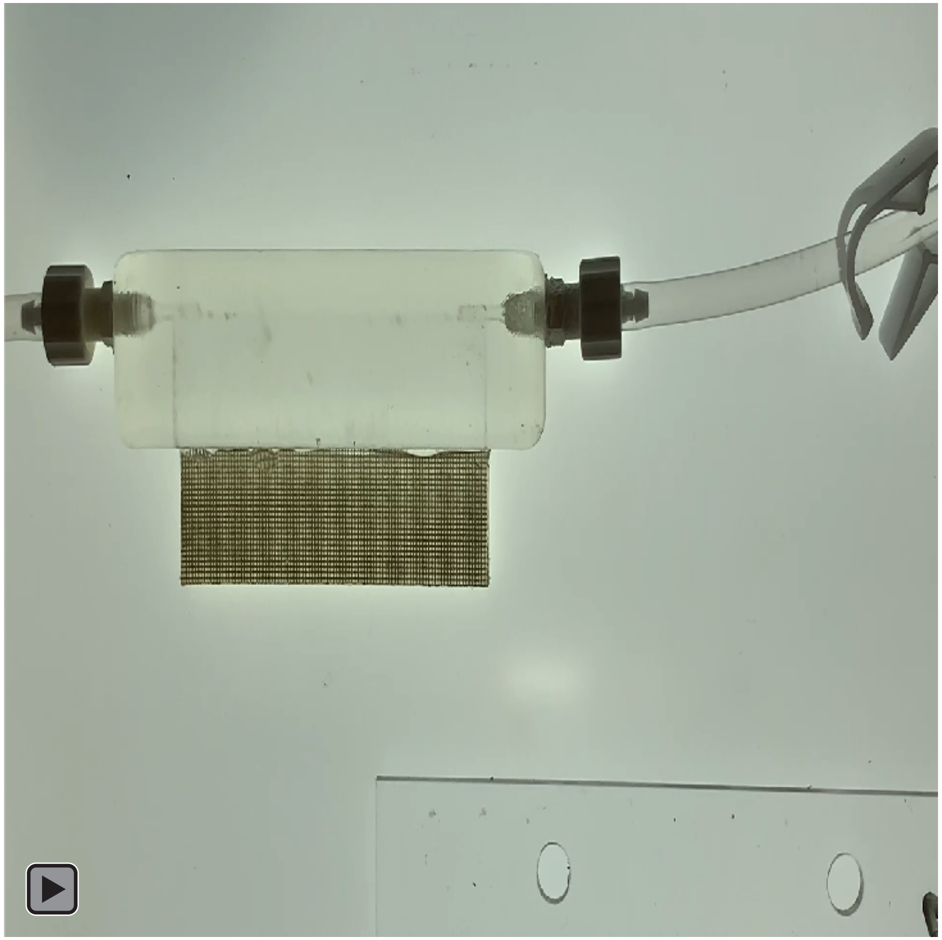
- **4 Identified flow regimes:**
  - Stable: Continuous liquid stream at outlet, Q_{max} ~ 0.4 ml/s
  - Ingestion: Gas ingested at outlet
  - Embolism: Accumulation of liquid at inlet
  - Ejection: Liquid droplet ejection from channel



Ingestion



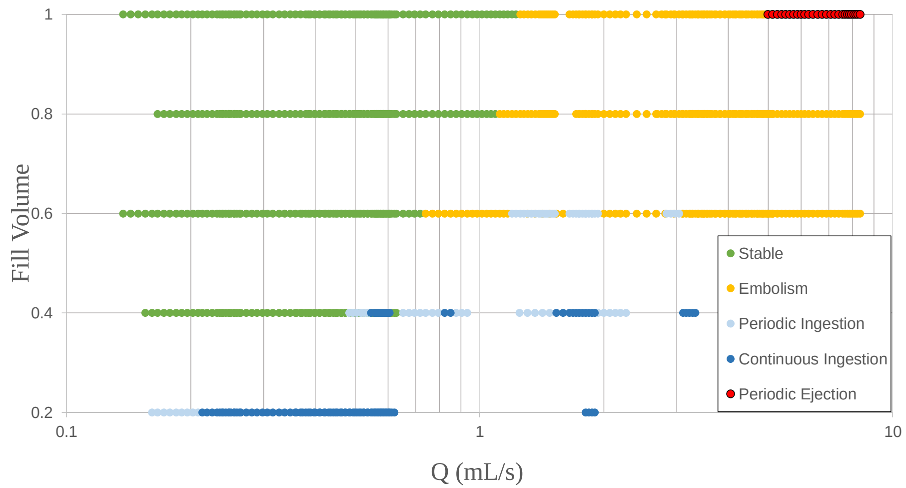
Embolism/Ejection



Key Questions and Impact on Advancing the Field

- **Where are the operational limits for 1g vs low-g stability regimes for poorly wetting liquids such as contaminated/sugary water?**

Hydroponics system regime map with a single taproot in 1g lab testing



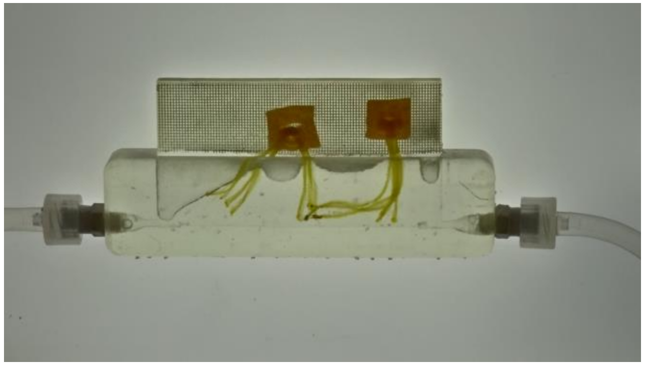
Need: Providing plants with ready access to both air and water remains a significant issue. The lack of convective mixing has implications for the movement of water, oxygen and solutes through the root zone. Most plants returned from microgravity have experienced some degree of hypoxia stress or root zone solute stress.

Application: Long-term food production systems for missions to the Moon and Mars, as well as the immediate need for ISS food supplements to the crew diet. PWM will demonstrate the low-gravity role of surface tension, wetting, and system geometry to effectively replace the role of gravity in certain terrestrial plant growth systems.

Benefits/Spin-off Applications

- **Space:**
  - Increased confidence for capillarity as a method of containment (PWM is in open cabin air with removable lid)
  - Increased knowledge of flow regime maps for poorly wetting liquids, and ISS environment's influence on evaporation rates
  - Potential to influence next generation of space food production systems for ISS, Moon, and Mars

- **Earth Benefit**
  - Optimization of water uptake, thermal balance, etc. has direct application to terrestrial plant growth systems
  - Scale models can easily be manufactured to demonstrate low-g fluid behavior in 1g environment



1/3 Scale, horizontal flat model for 1g testing or capillary phenomena

Future Plans

- **PWM-01 Soil and PWM-02 Hydroponics**
  - Currently on ISS, ops TBD?

- **PWM-03 Root Accommodation Zone**
  - Further Developed Hydroponics section with root growth channel

- **PWM-04 Parallel Hydroponic Trays**
  - Parallel hydroponics trays to address full system stability for multiple plants

- **PWM-03 & PWM-04 expected to launch on SpaceX CRS-21 next year**

- *Many thanks to the KSC Plant Biology Team: Gioia Massa, Oscar Monje, Ralph Fritsche, Tom Dreschel, and others*

Backup Charts

PWM Test Matrices

- **Soil (3 modules)**

Plant	Test Loc Setup	Test Setup incl gather + video	Fill + still (Crew Time)	Beginning of Foliage Sat (hr) (no extra Crew Time)	Top Up Task List? (Crew Time)	Refill (Crew Time)	Battery Change (Crew Time)	Teardown + Stow (Crew Time)	Approx Fluid Volume Total 48 hr (mL)
Fast	0.5	1.5 hr	1	1.5	0.5	0.5	0.25	1 hr	325/350
Medium	0.5	1.5 hr	1	3	n/a	n/a	0.25	1 hr	126 mL
Slow	0.5	1.5 hr	1	7	n/a	n/a	0.25	1 hr	126 mL

- **Hydroponics (1 module with several plant types over 2 days)**

Plant Type	Number of Plants	Plant Position	Time (hr)	Note	Approx Max Fluid Volume Total per day (cut foliage) (mL)	Approx Max Fluid Volume Total per day (uncut foliage) (mL)
n/a	0	n/a	1	stable	120	250
PWM-H-C	1	2	1	Stable	120	250
PWM-H-C	2	1, 2	1	stable	120	250
PWM-H-C	2	1, 2	0.5	Ingestion	120	250
PWM-H-F	1	2	1	Stable	120	250
PWM-H-F	2	1, 2	1	Stable	120	250
PWM-H-F	3	1, 2, 3	1	Stable	120	250
PWM-H-F	3	1, 2, 3	0.5	ingestion	120	250

Issues

- Fast-to-flight
  - During development, seemingly small issues can have a major impact on schedule
  - 3D printed model crack during assembly
  - However, quick turnaround from ATP to FHA (13 months) provides huge science payoff (increased TRL in relevant environment)
  - Lessons learned and downlinked data will inform PWM 3 & 4 designs, scheduled to launch to ISS on similarly quick schedule

PWM Microgravity Requirements

- **Design is stable for disturbances up to 10^{-2} g, most common perturbations are 10^{-4} g**
- **Stability: water will remain in *open container* test cell due to surface tension forces**
- **Numerical interface stability work is still underway**
- **Upscaling design is dependent on the g environment**
- **ISS cabin relative humidity and air temperature will be obtained post-experiment**