National Aeronautics and
Space Administration

Plant Water Management in Microgravity

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Project Scientist
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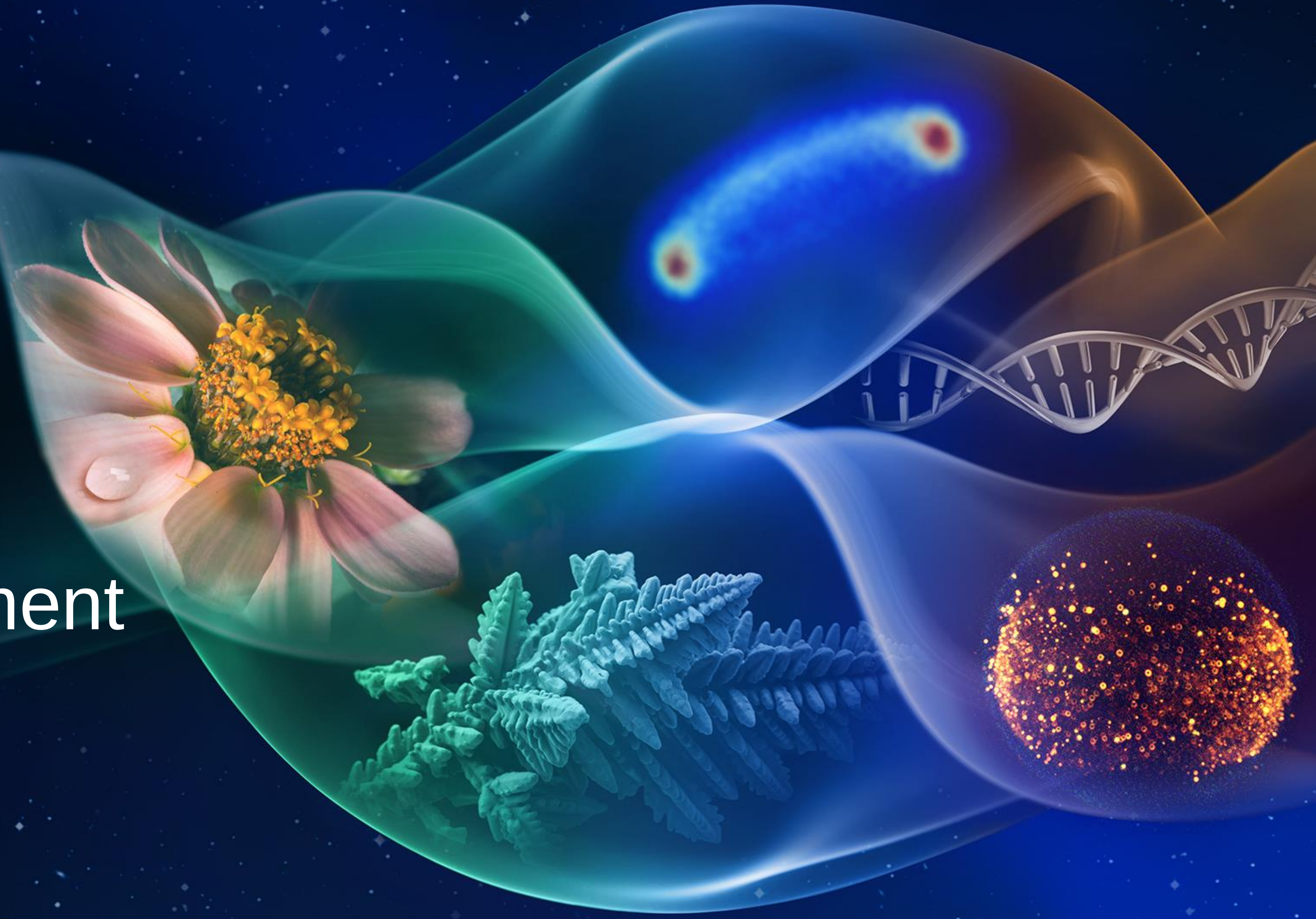

Overview

- Plant Water Management Team
- Background
- Concept Development
- ISS Experiments
- Data Analysis
- Future Plans

PWM Team Contacts

Name	Role	Affiliation	Email
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Science Background

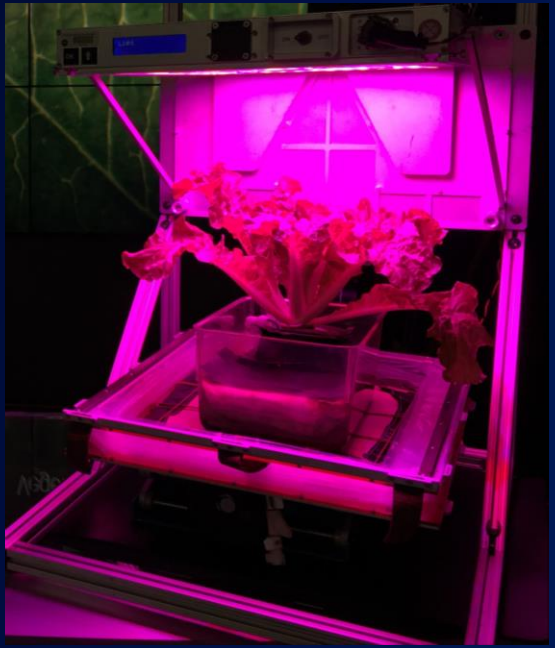
<u>NASA’s Plant Water Management Challenges</u>

- **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.**

Example of plants grown on the ISS

Existing Work: VEGGIE & PONDS

- **The Vegetable Production System (Veggie) is a plant growth unit on the International Space Station.**



- **The Veggie concept is a simple, low-power system to grow fresh, nutritious food for our astronauts to supplement their diet and use as a tool to support relaxation and recreation. Veggie utilizes passive wicking through soil to provide water to the plants as they grow. Currently, the seeds are glued into, emerging from the top of a plant pillow.**

- **Veggie PONDS (Passive Orbital Nutrient Delivery System) was a follow-on effort to improve the waer delivery methods of the Veggie system**

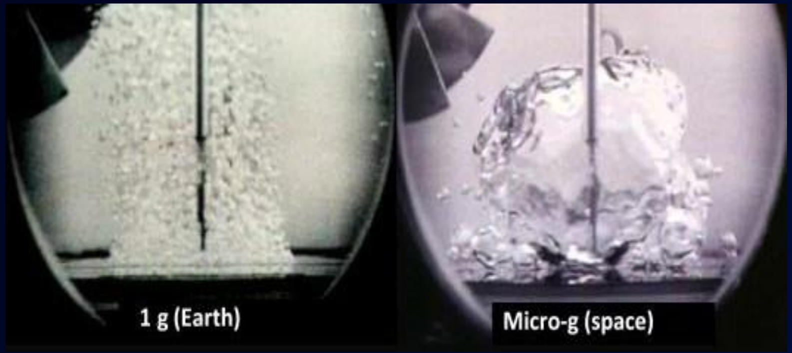
Existing Work: APH

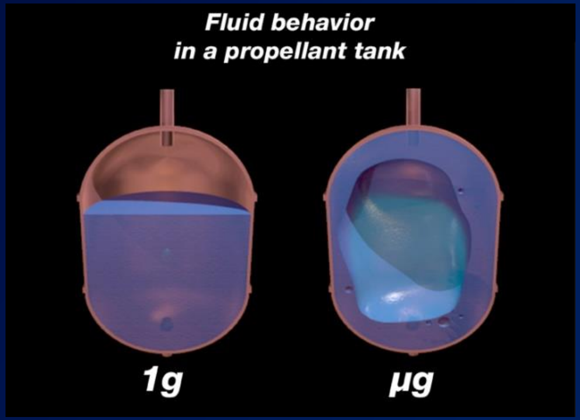
- **Advanced Plant Habitat (APH) is a facility that provides multiple levels of control over the growth environment**
- **Similar to Veggie system in that it still uses arcillite-based soil, but with porous tubes for wetting rather than wick structures**
- **Culmination of VEGGIE, PONDS, shuttle experiments, etc**

Significance of Fluids Management

Virtually all major systems involve fluids management (or mis-management) in microgravity

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





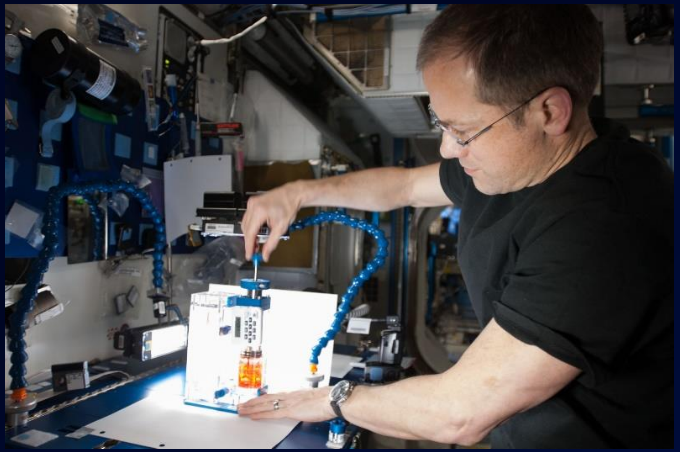
PWM Science Objectives

- **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

Rationale

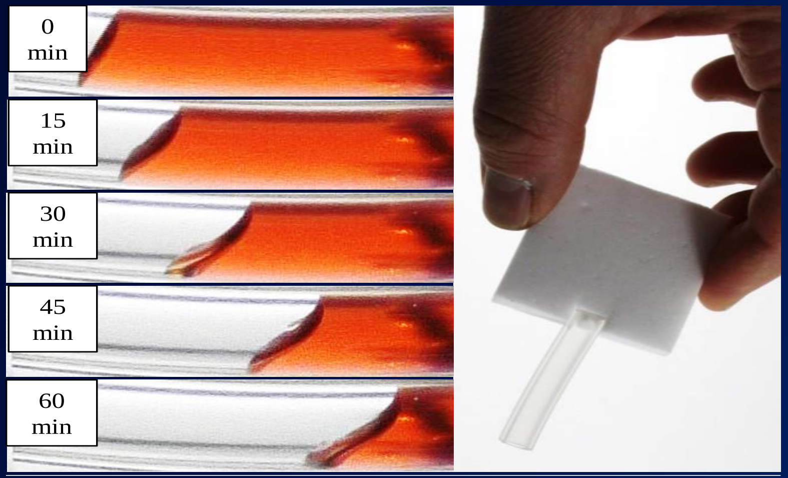
- PWM is conceptually similar to Capillary Flow Experiments (CFE) and CSELS (Capillary Structures for Exploration Life Support), both led by the same PI
- PWM is a further demonstration of capillary methods for applied fluid control, potential path forward is known
- Reutilizing similar or identical 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



Importance and Reason for ISS

Duration of microgravity test conditions for fluid physics demonstrations:

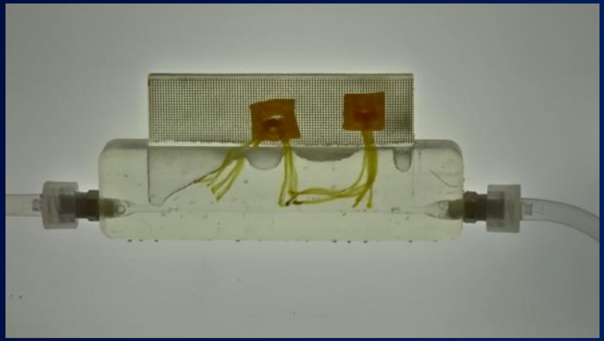
- **System prime and steady-state stability in complex micro-g geometry**
- **Allows establishment of steady pumped flow with evaporation on timescales that cannot be achieved in drop towers or aircraft.**
- **Crew tended experiment**
  - Extra science potential for g-jitter stability response, bubble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



CSELS Experiment example of long-duration evaporation rate testing

PWM Ground Work

- Initial studies focused on methods for aerating the soil using arcillite and other porous media, along with ways to simulate plant roots/evaporation using felts and sponge material, for both soil-based and hydroponics
- Scaling approximations were used to study microgravity behavior in terrestrial benchtop lab spaces, using capillary length



- Relates gravity and surface tension (Laplace Pressure)

$$P_h = \rho g h = 2\rho g \lambda_c$$

$$P_\gamma = 2\frac{\gamma}{\lambda_c}$$

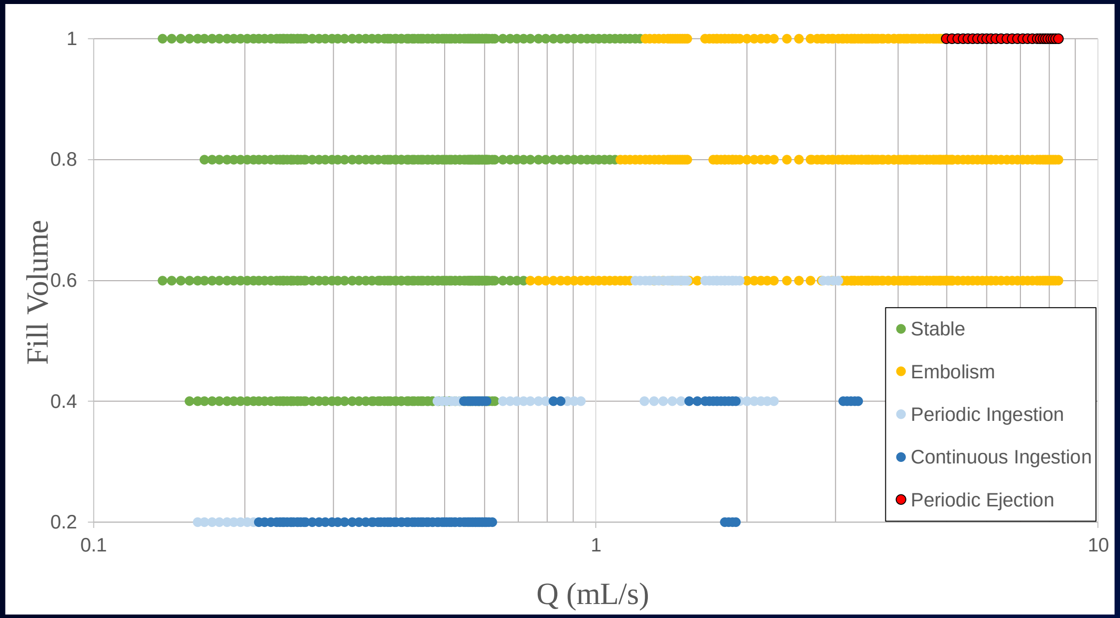
- Capillary length for water in 1g is ~3mm

  (essentially 2D demonstrations)

$$\lambda_c = \sqrt{\frac{\gamma}{\Delta\rho g}}$$

PWM Ground Work

- Drop tower tests were used to verify system stability and establish basic regime maps by pinpointing flow rates of interest (eg, ingestion, embolism)
- Operational limits for 1g vs ug stability regimes were established for poorly wetting liquids such as contaminated/sugary water
- Water migration issues present in Veggie in simulated root structure fed into model iteration



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

Test Fluid / Soil Properties

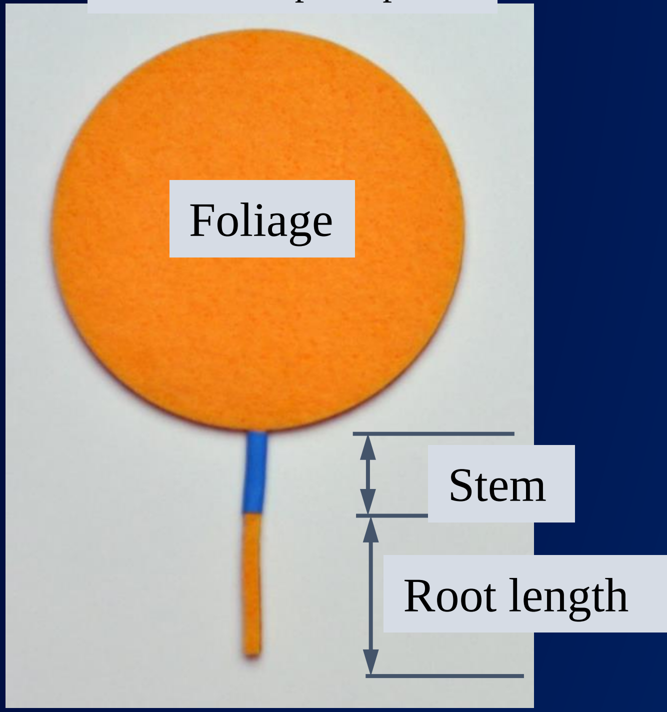
- **PWM Test Fluid**
  - Ersatz plant nutrient solution of water mixed with fruit drink mix
  - Sucralose sweetener included in drink mix
  - Kinematic viscosity: 1 CS
  - Benefits:
    - Flow visualization
    - Poorly wetting fluid (sweetened water)
    - Mixed solution similar to plant nutrient mix
    - Tox 0 – Approved by JSC toxicology and MSFC ECLSS groups

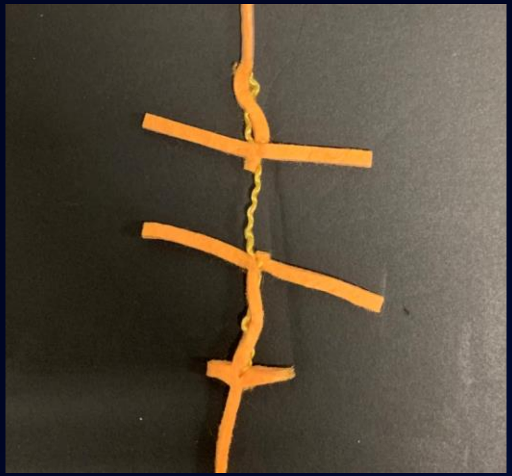
- **PWM Soil**
  - Arcillite
    - Commonly used as soil basis for prior NASA plant growth systems such as VEGGIE, PONDS, APH, etc.
    - Calcinated clay particles, highly wetting when dry, clumps when saturated
  - Breathable Soil
    - Nonwetting hydrophobic media
    - Aerating soil in contrast to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

Simulated Plant Properties

- **PWM Simulated Plants**
  - – 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

Simulated taproot plant

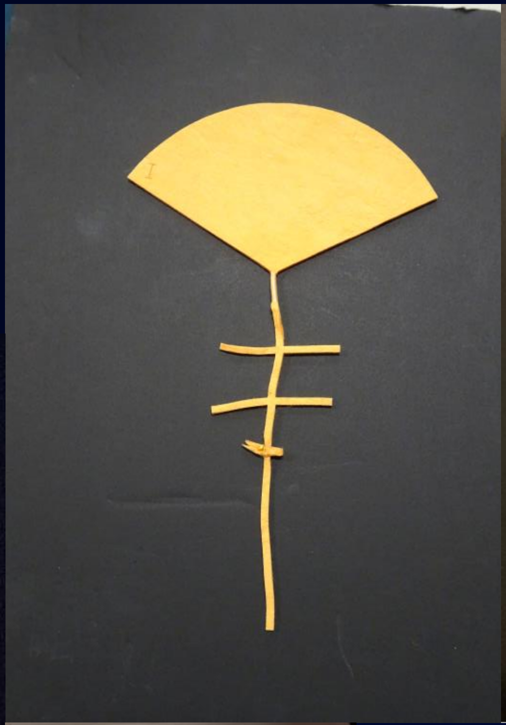


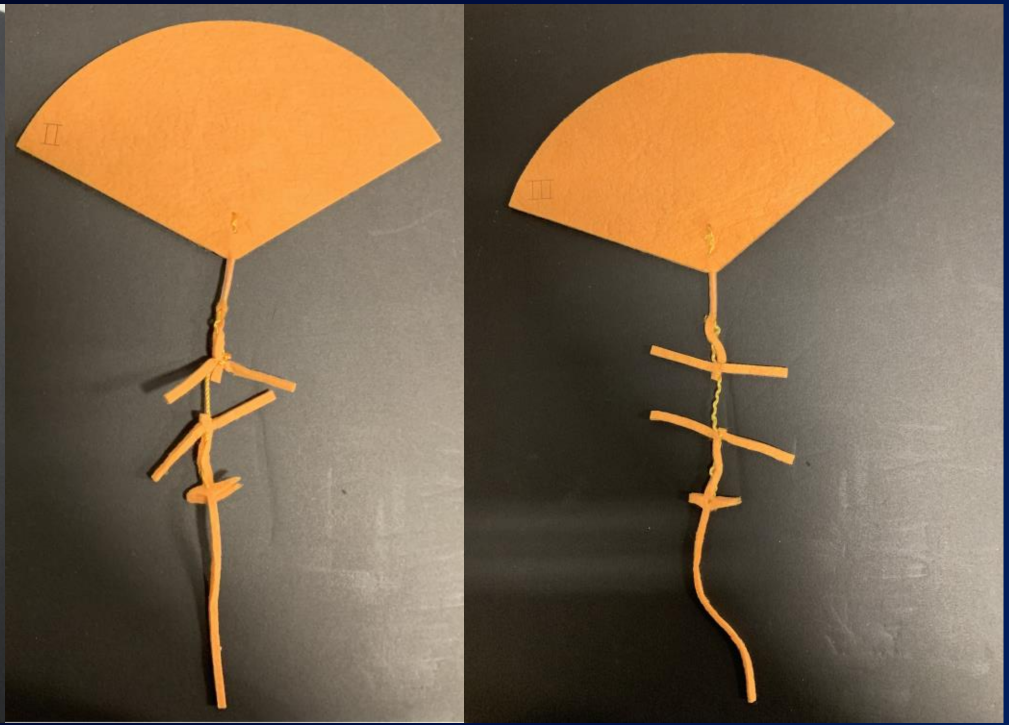


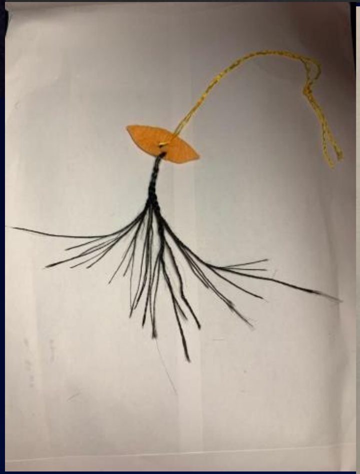
Simulated "germination" plant root structure with throttled uptake

Simulated fibrous root plant

Simulated Plant Variety







Implementation

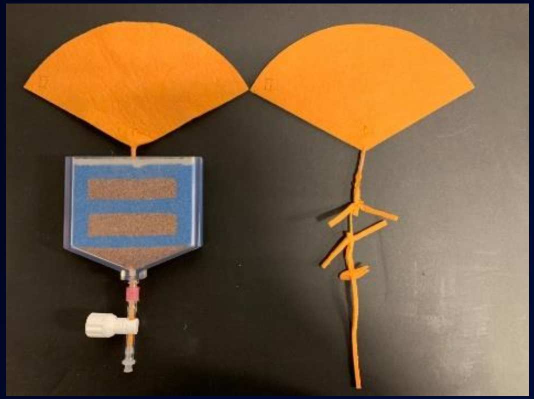
Watering Schemes and Factors:

1. Soil
2. Hydroponics
3. Root Accommodation Zone Hydroponics
4. Parallel Hydroponic Trays
5. *Advanced Capillary Methods - TBD*
6. *Humidified Root Zone - TBD*

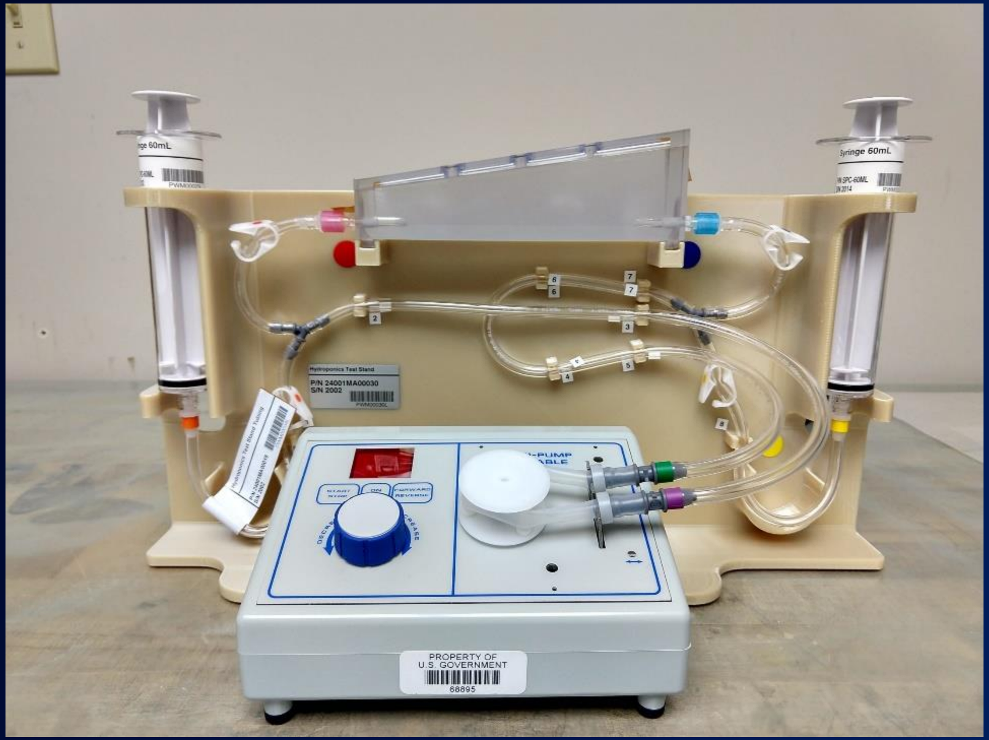
Test Facility:

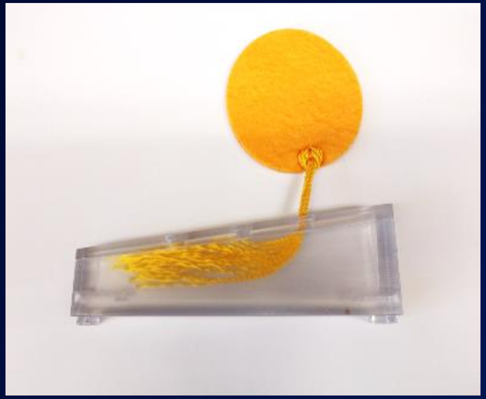
- Maintenance Work Area (MWA) on ISS
- Crew Involvement
  - Setup
  - Priming
  - Adjusting Flow Rates
  - Dispose of hardware after use
- Data Analysis based on Downlinked Images

PWM 1 (Soil)

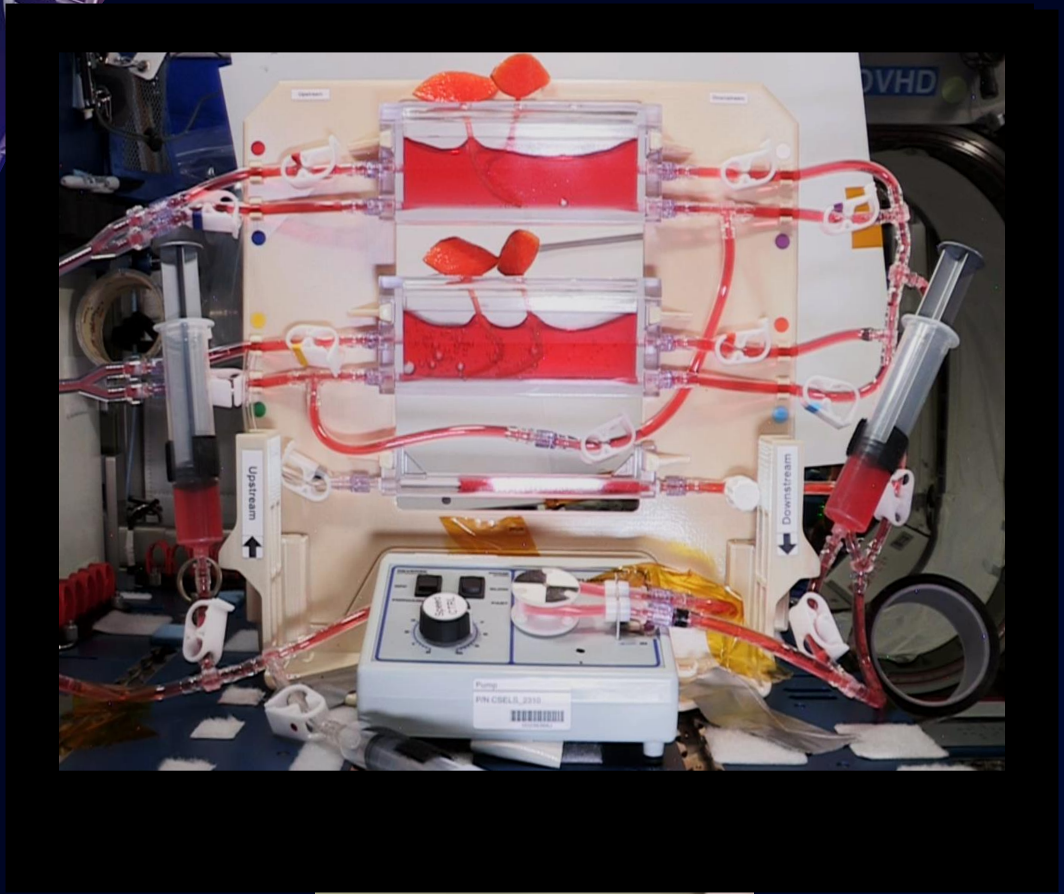


PWM 2 (Hydroponics)

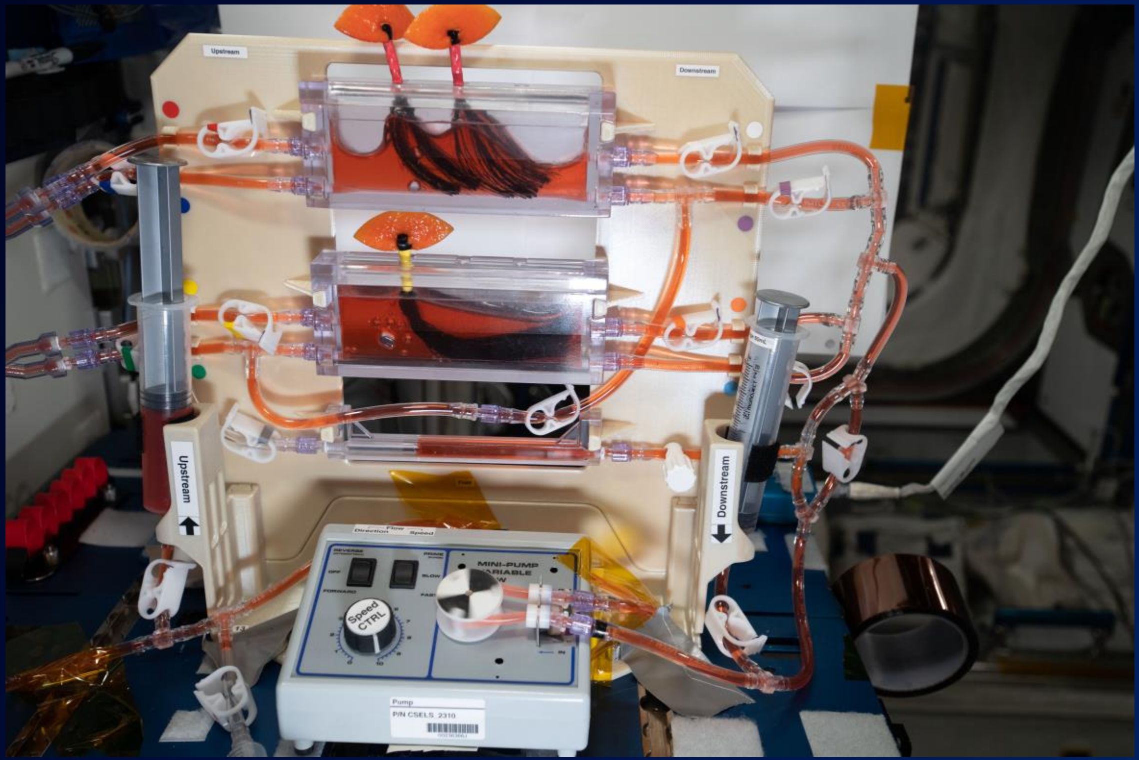




PWM 3 (Wedge)



PWM 4 (Cylinder)



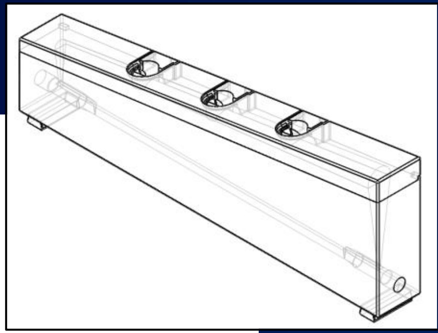
ISS Operations

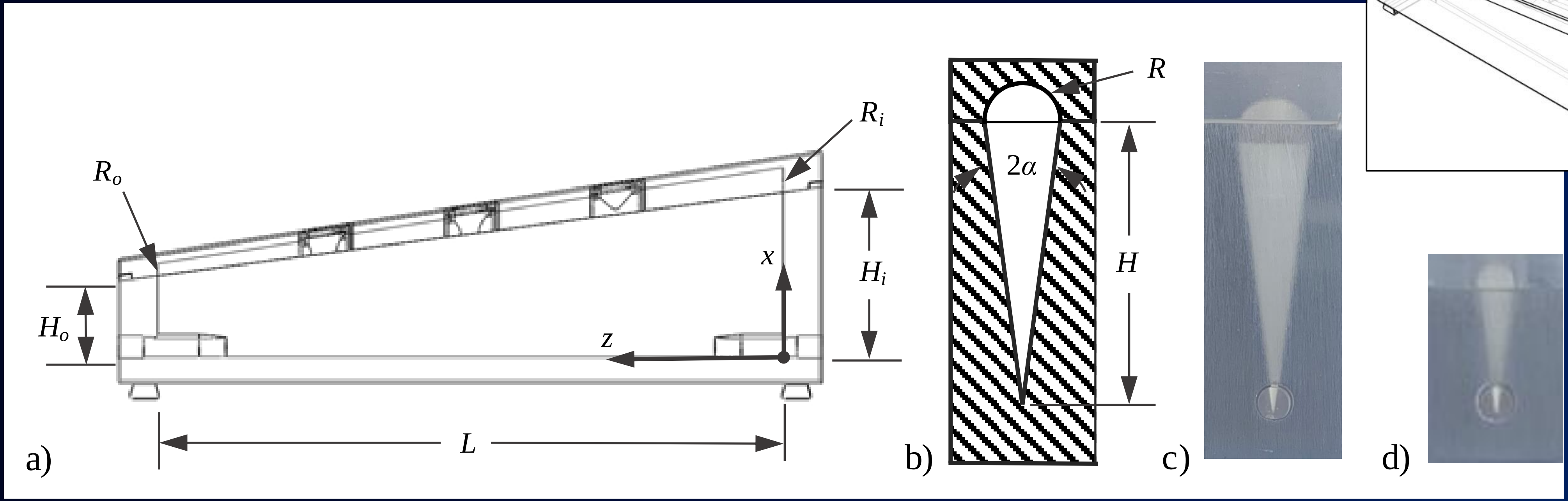
- **PWM-01 Soil and PWM-02 Hydroponics**
  - Completed ISS ops in Feb ’21
- **PWM-03 & PWM-04 Advanced Hydroponics**
  - Completed ISS ops in July ‘21
- **14 separate operations events, 6 days of soil, 8 days of hydroponics, 9 crew members**

- **Established regime map (steady, ingestion, min/max flows) in hydroponics**
- **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**
- **Ebb/flow technique established as most promising method for hydroponics**

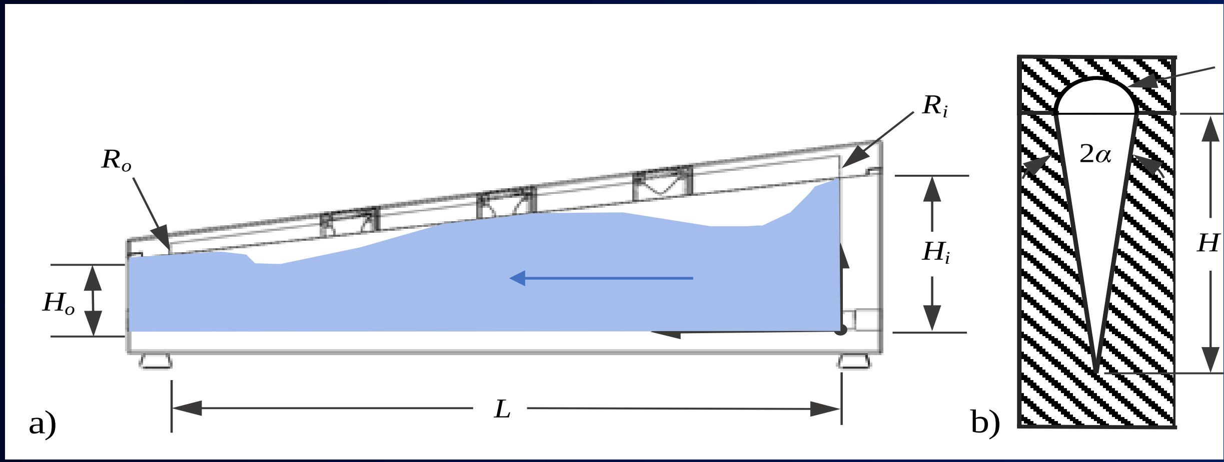
Hydroponics Analysis

- **Governing Equations based on ISS Capillary Corner Flow Experiment (~2013)**
- **Use Concus-Finn critical contact angle to control liquid position**
- **θ = 82.5° < π/2 - α , α = 7.5° half-angle interior corner channel**





Hydroponics Analysis



- **Liquid Interface Position *h***

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

- **Flow Rate *Q*:**

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

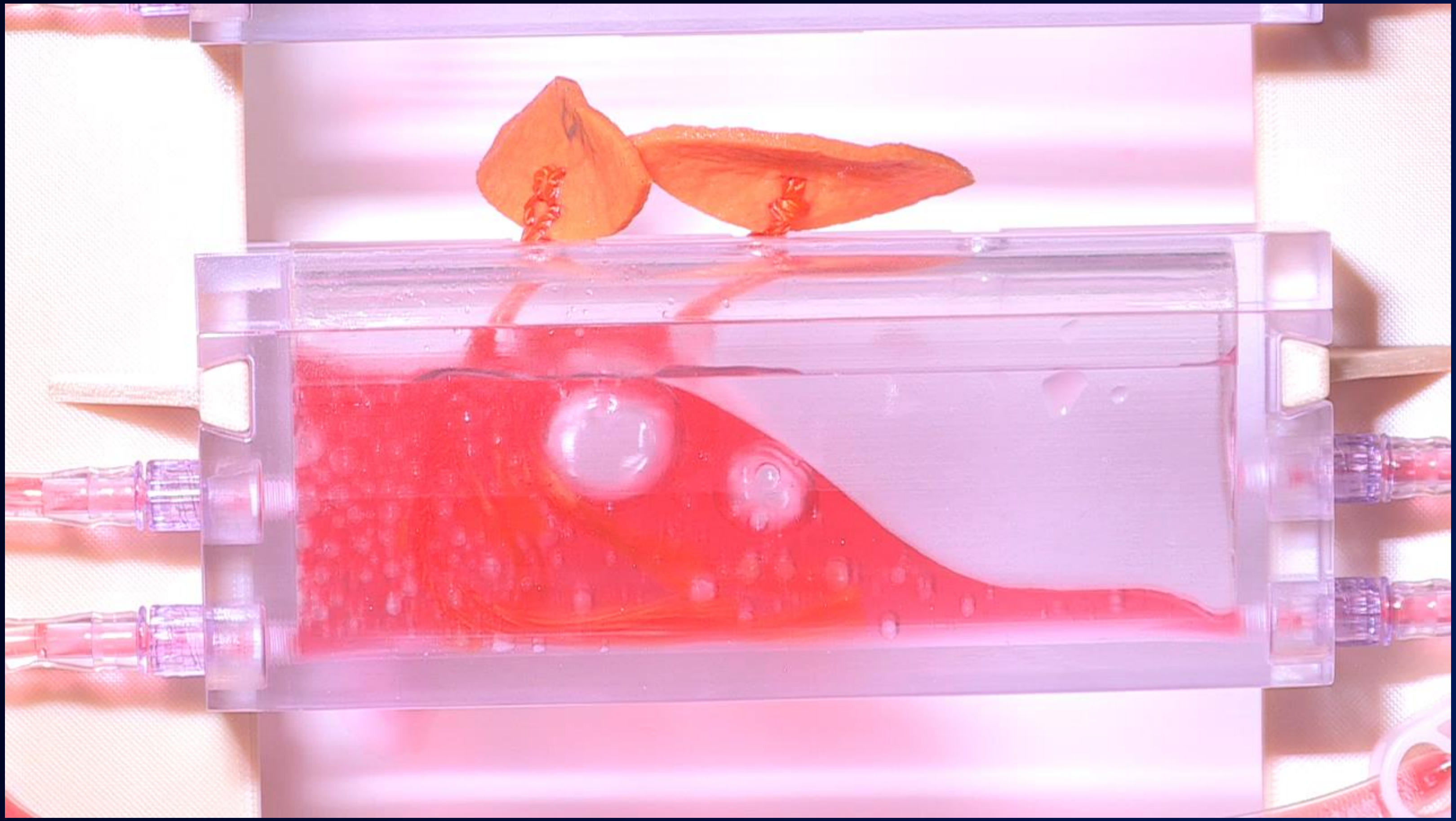
•**The term $F_i \approx 1/7$ is a dimensionless flow resistance parameter**
•**F_A and f are dimensionless area and free surface curvature functions**

$$F_A = f^2\left(\frac{\cos\theta\sin\delta}{\sin\alpha} - \delta\right) \sim \tan\alpha \qquad f = \frac{\sin\alpha}{\cos\theta - \sin\alpha} \qquad \delta \equiv \pi/2 - \alpha - \theta.$$

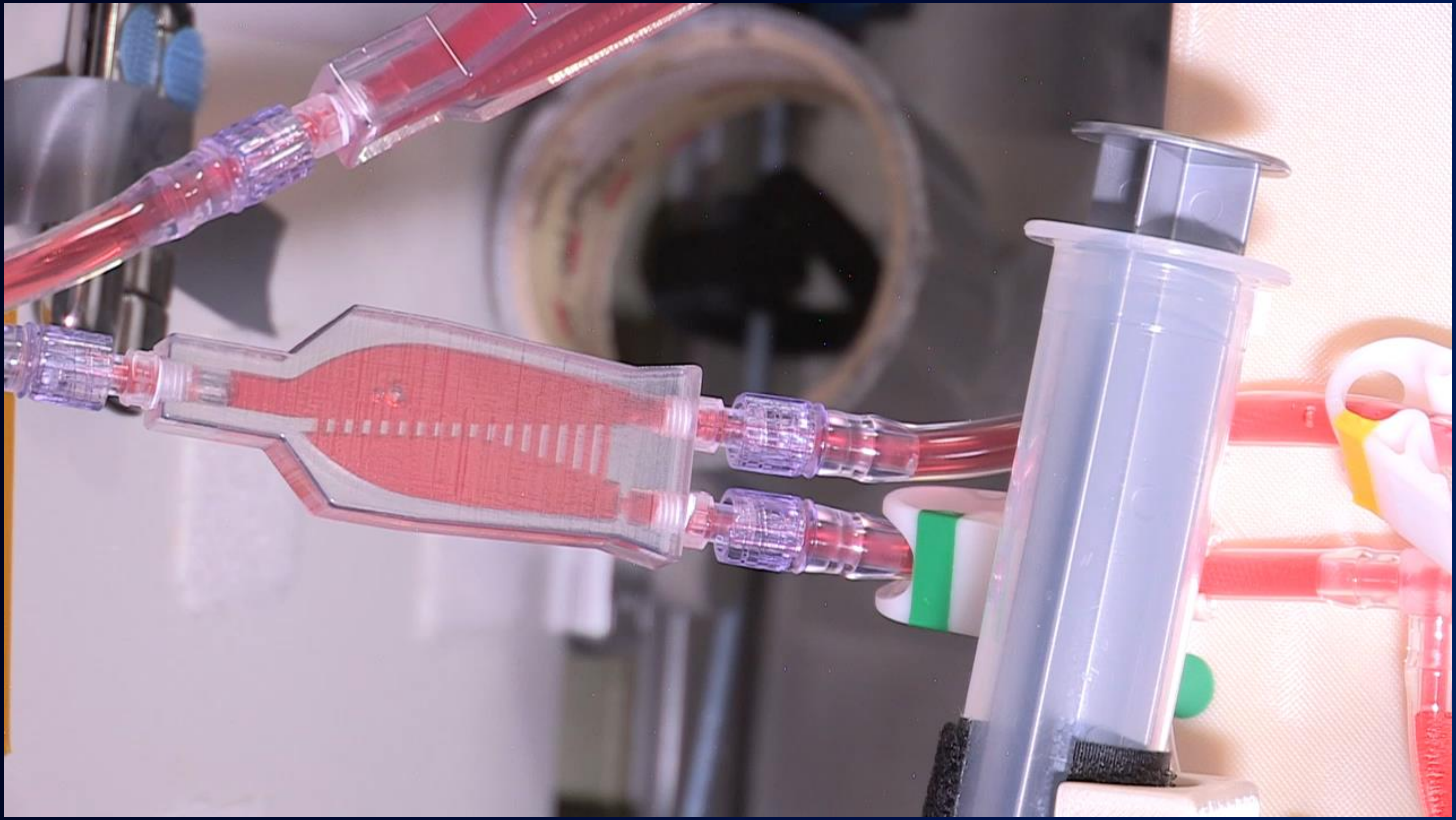
- **Pressure is driven by the contact angle / radius of curvature, all capillary driven for this case, which allows for passively driven flow**

Hydroponics Analysis

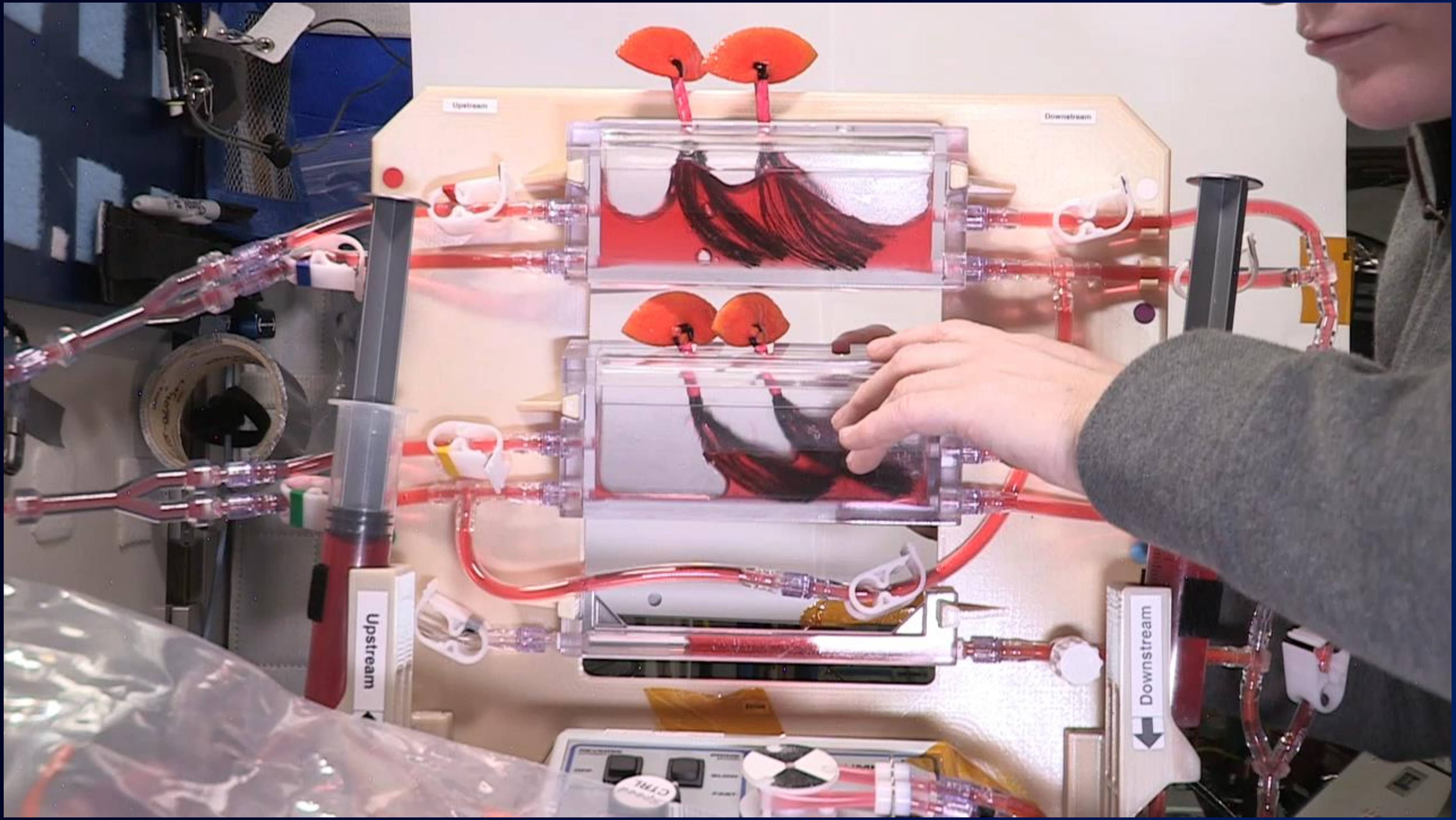
- **Knowing these values and the operating regimes, the ISS experiment allowed testing of bubble ingestion for possible aeration of the root zone**



Hydroponics Analysis: Bubble Separators

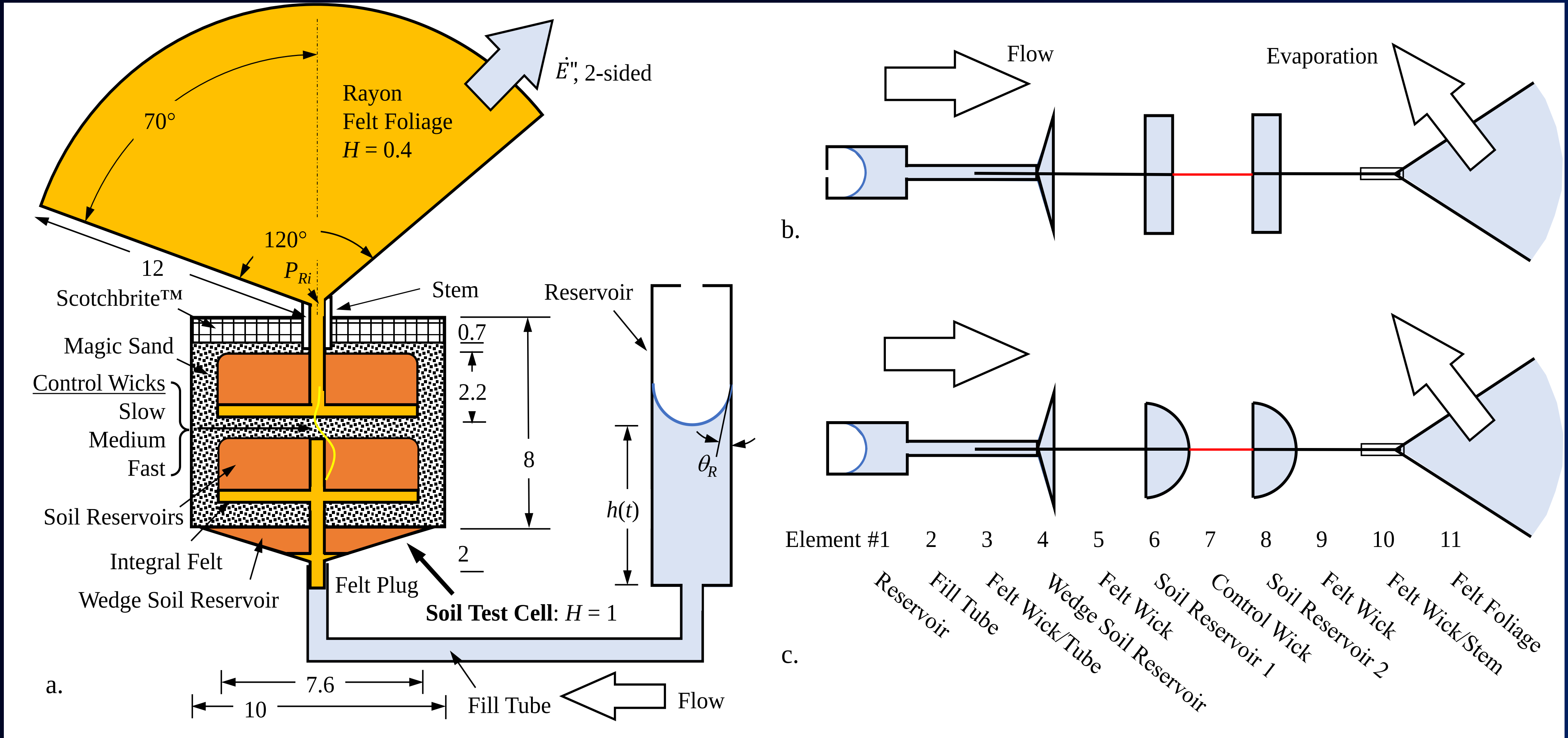


Hydroponics Analysis: Containment



Soil Sample Analysis

- **Annotated schematic of PWM Soil test unit (dimensions in cm) with fluid element model and simplified mathematical model.**



Soil Sample Analysis

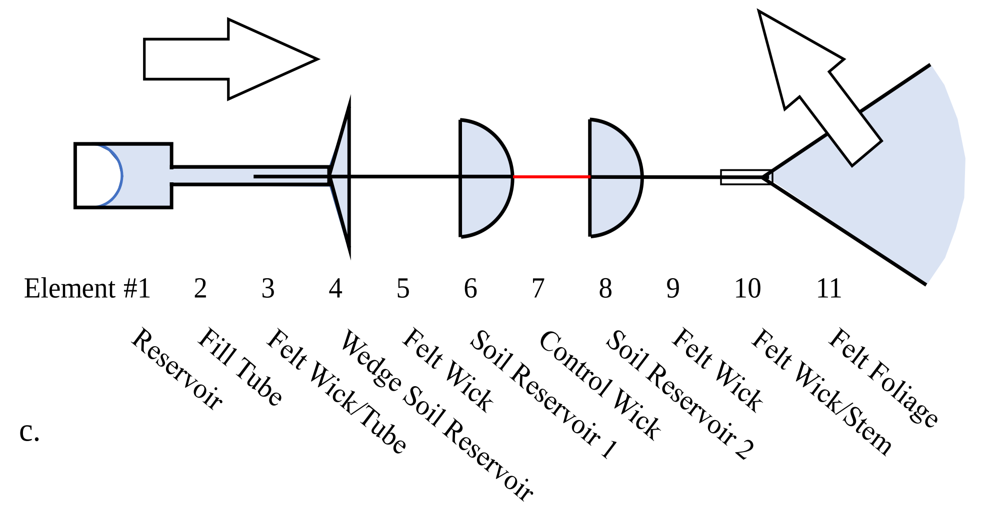
For quasi-steady fully-developed laminar flows it may be shown that the pressure drop is governed by:

$$\Delta P \sim \mu\, U\, L \,/\, r_p^{\,2} = \mu\, Q \cdot L \,/\, A\, r_p^{\,2}$$

where characteristic properties are dynamic viscosity μ, local characteristic velocity U, volumetric flow rate through the network Q, element length L, cross-sectional area A, and effective element pore radius r_p. Because μ and Q are constants for all elements, we employ:

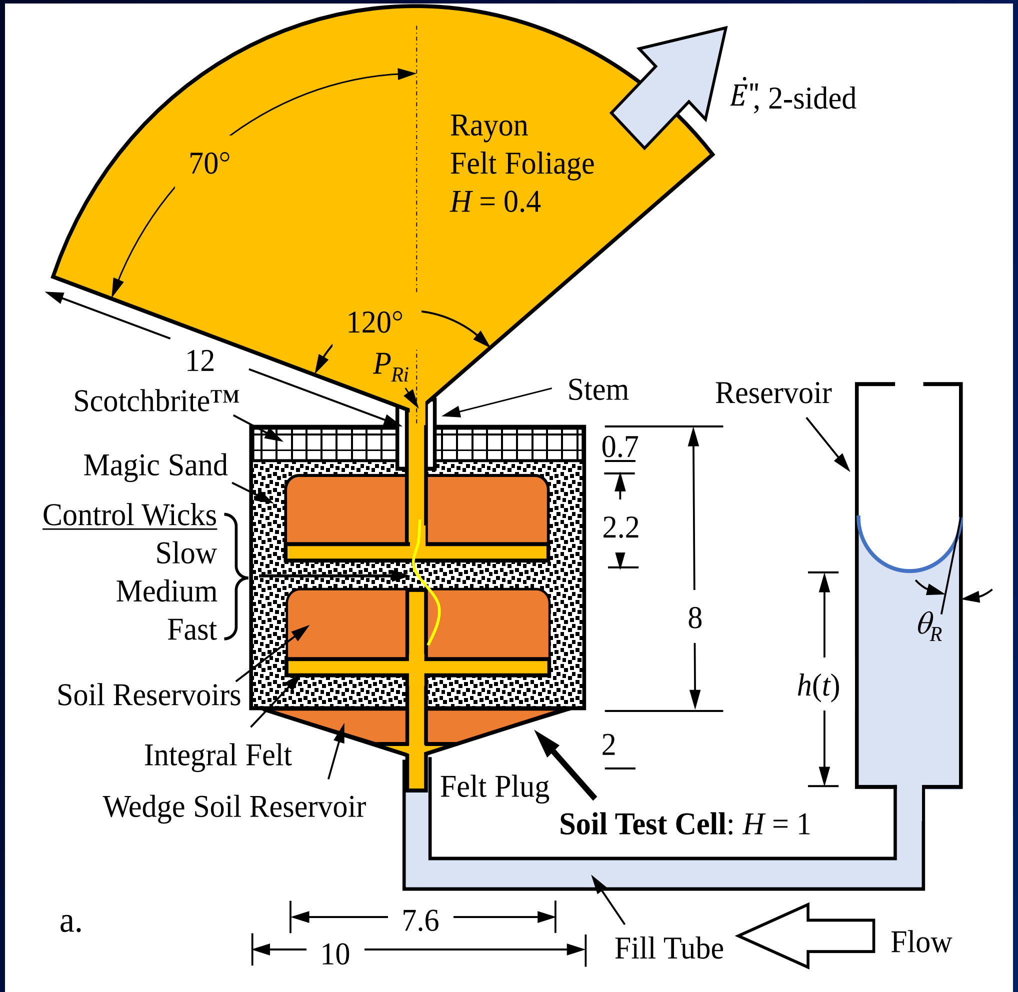
$$\Delta P/\mu Q \sim L/Ar_p^{\,2}$$

$L/Ar_p^{\,2}$ can be calculated to find the effective viscous resistance of each step



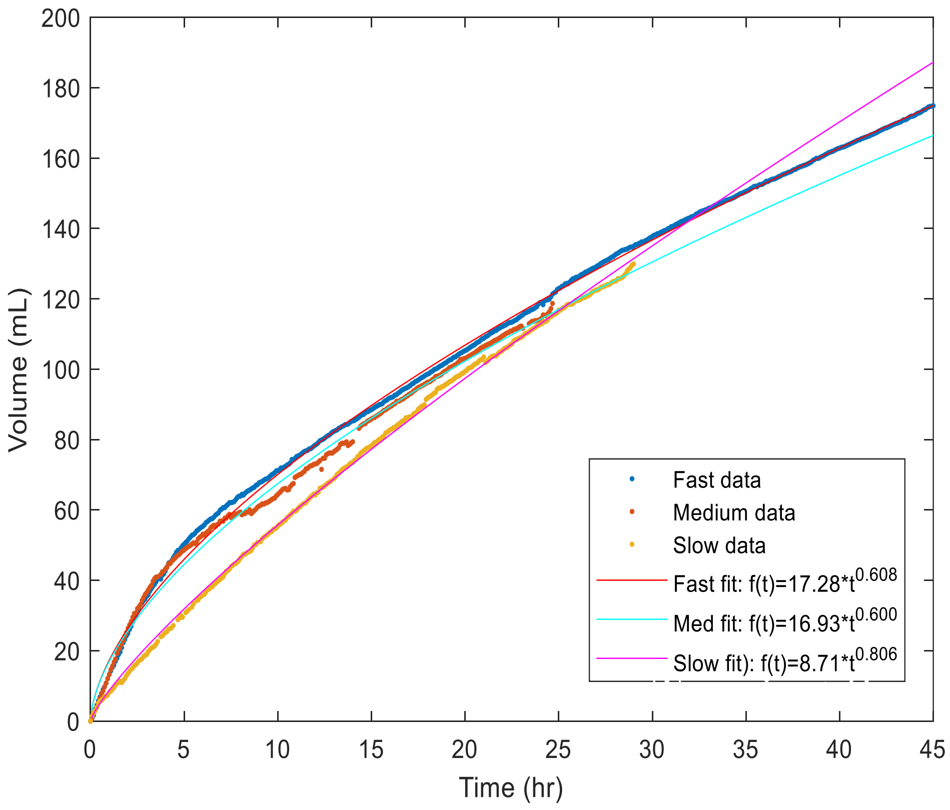
Soil Sample Analysis

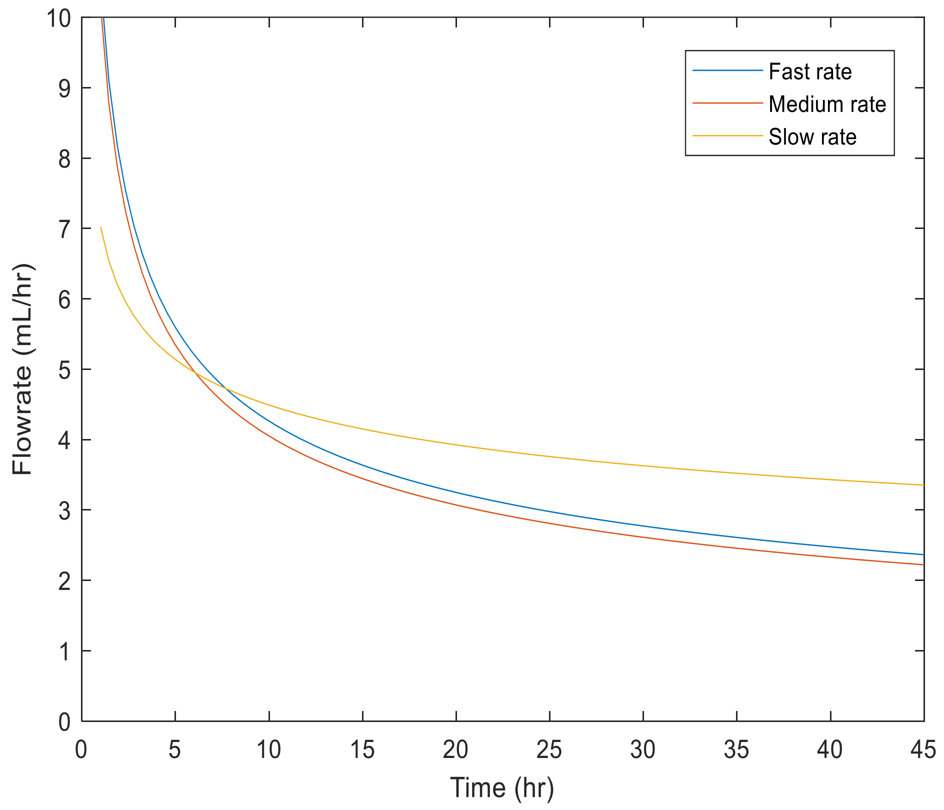
- 3 Different soil test unit were employed, for fast, medium, and slow uptake rates using different control wicks.
- The soil reservoirs contribute a total of 5%, 15%, and 19%, respectively. The foliage contributes 11%, 36%, and 46%, respectively.
- Despite the fourfold increase in resistance between Medium and Fast elements, the overall resistance is only 25% higher for the former (8,263 vs 6,563). The Slow PWM Soil Test Cell provides up to fourfold higher flow resistance than the Fast Test Cell (26,063 vs 6,563)



Resistance units in 10^{-3} cm $^{-3}$

Soil Sample Analysis





Transient Reservoir volume losses during capillary infill of PWM-Soil Fast, Medium, and Slow test cells with data collected on 5 min intervals. The Fast test cell run included two reservoir refills while the Reservoir for Medium and Slow runs was not refilled.

Transient flow rates from smoothed data in a. of 169.6 ± 6.6 mL/hr·m^2 a 22 °C and 42% relative humidity. For the PWM-Soil Foliage area of 305 cm^2 at 22.5 °C and 42% relative humidity, we estimate a steady saturated Foliage evaporation rate of ≈ 5.2 mL/hr

Future

- PWM 5&6 science requirements are currently in development
- **Space Benefits:**
  - Increased confidence for capillarity as a method of containment
  - 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
- **Earth Benefits**
  - Scale models can easily be manufactured to demonstrate low-g fluid behavior in 1g environment
  - Optimization of water uptake, thermal balance, etc. has direct application to terrestrial plant growth systems

Many thanks to the KSC Plant Biology Team: Gioia Massa, Oscar Monje, Ralph Fritsche, Tom Dreschel, and astronauts pictured here!

Thank you!

NASA Astronaut Kate Rubins telling the team “that’s so cool” after finishing PWM work