

Microgravity Root Zone Hydration Systems



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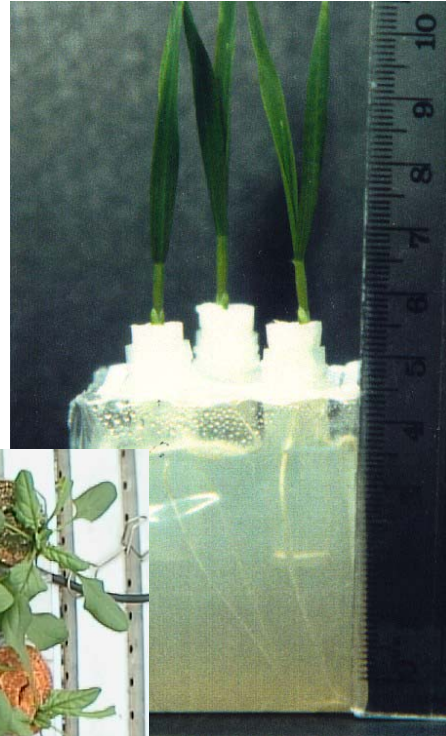
Root Zone Hydration - Requirements

- Supply adequate nutrient solution:
 - » Proper concentration, plant age and species dependent
- Proper water content and distribution:
 - » Microgravity capable and on-orbit start, adjustable for germination, imbibition, growth, harvest, system restart.
- Adequate gas exchange:
 - » O₂ supply, CO₂ removal, trace gas control
- Automation and control:
 - » Sensor feedback, adequate fine control, 3D-resolution
- Systems Integration and Optimization
 - » Minimize evaporation (-> dehumidification)
 - » Optimize aeration (-> chamber design)
 - » Minimize water content (-> mass)

Background

- Pre-loaded on Ground:
 - » Floral foam, germination paper, Rockwool™, Soil
 - » Solidified agar with gas exchange “nutrient pack”
 - » Water-Replenished Nutrient Pack
 - » Hydroponics substrates
- Active Control / Replenished:
 - » Hydroponics substrates with porous tubes
 - (Astroculture™, Zeolites)
 - » Porous tubes (bare) with seed interface
 - MPNE, PTIM

Options



Media Selection and Evaluation

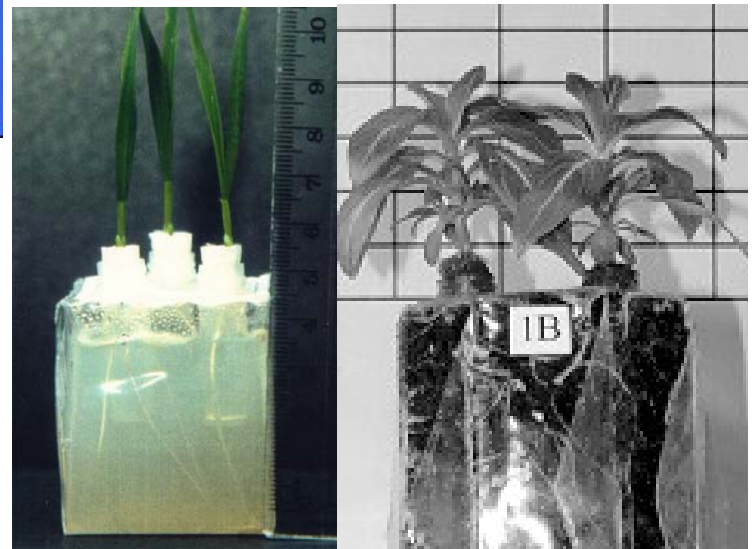
- Performance Difficulty to Test on Ground:
 - » Surrogate parameters
 - » 3-D sensor resolution
 - » Microgravity system incompatible with 1-g (hydrostatic p)
- Initial Priming (Unsteady):
 - » Wicking (distance, water column height)
 - » Uniformity of Wetting
- Water Transport (Steady state):
 - » Maintain constant water content
 - » Maximum sustainable flow rate

PGBA with Water-Replenished Nutrient Packs

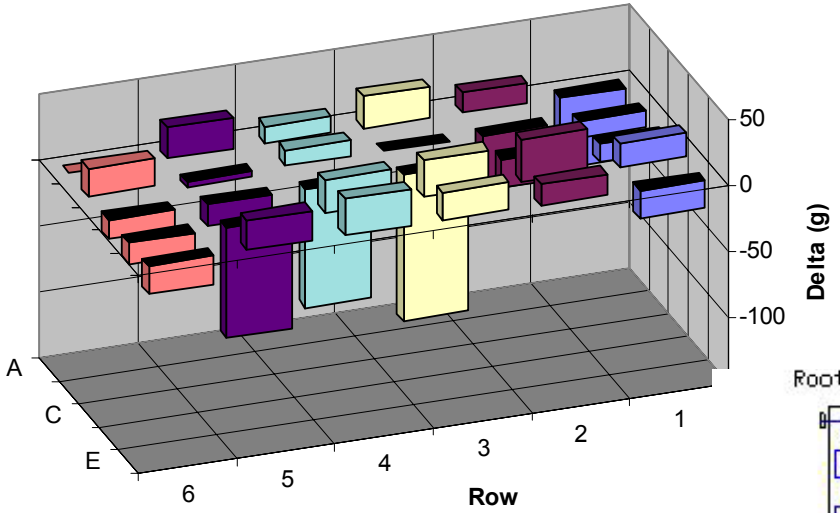


Nutrient Pack Design by:
Dr. A.G. Heyenga

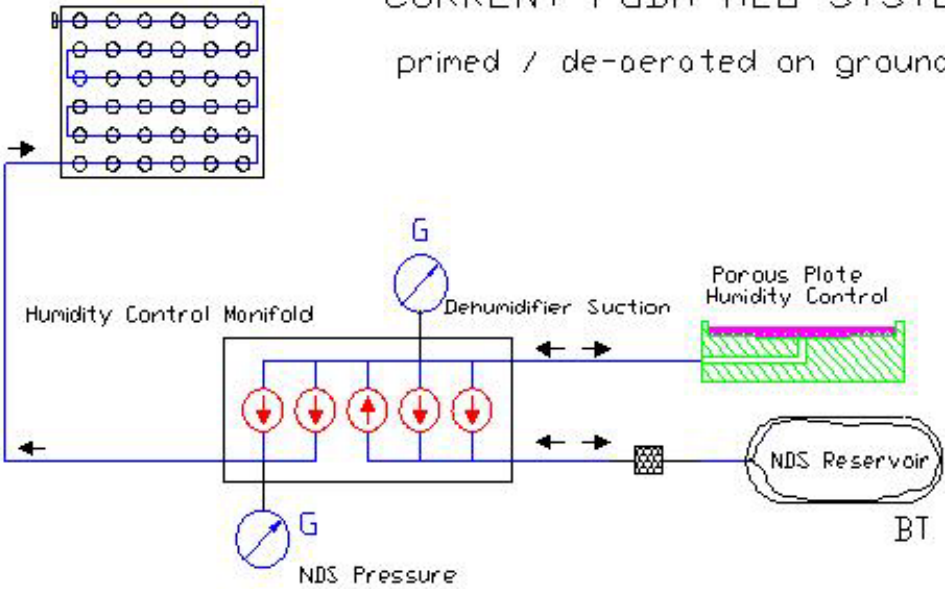
- Gas-permeable enclosure
- Aeration in close proximity (< 5 cm).
- Any substrate / composition
- Easy and modular for flight preparation.
- Pathogen control



Nutrient Pack – Moisture Maintenance

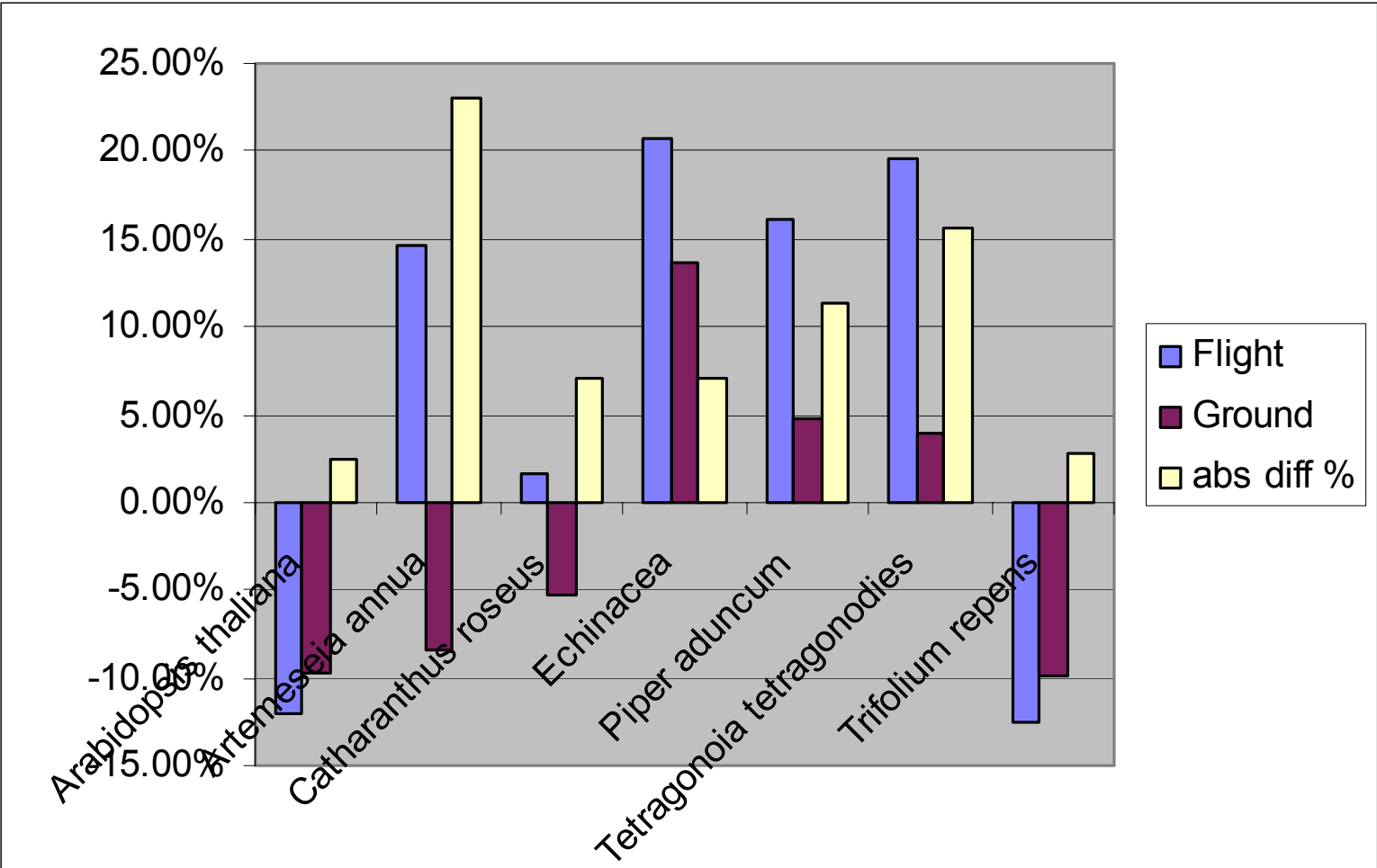


Root Tray Distribution

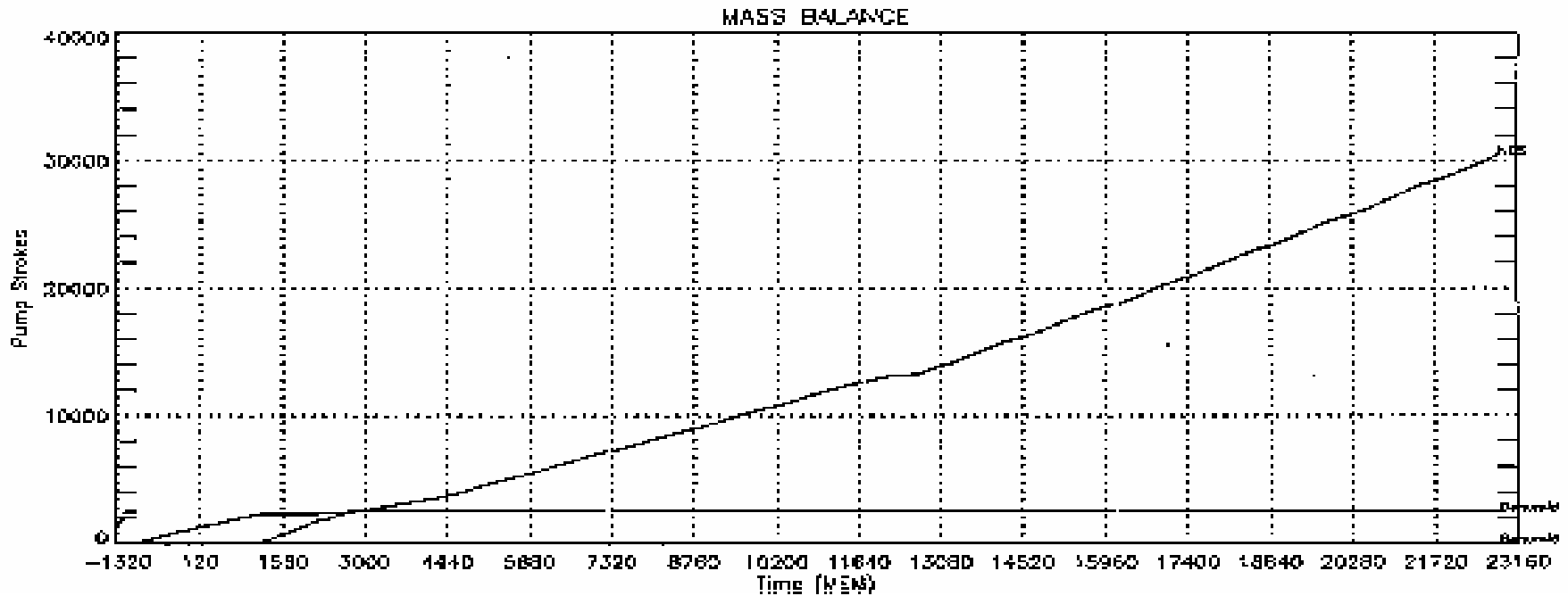


CURRENT PGBA H₂O SYSTEM
 primed / de-aerated on ground

Nutrient Pack – Moisture Maintenance



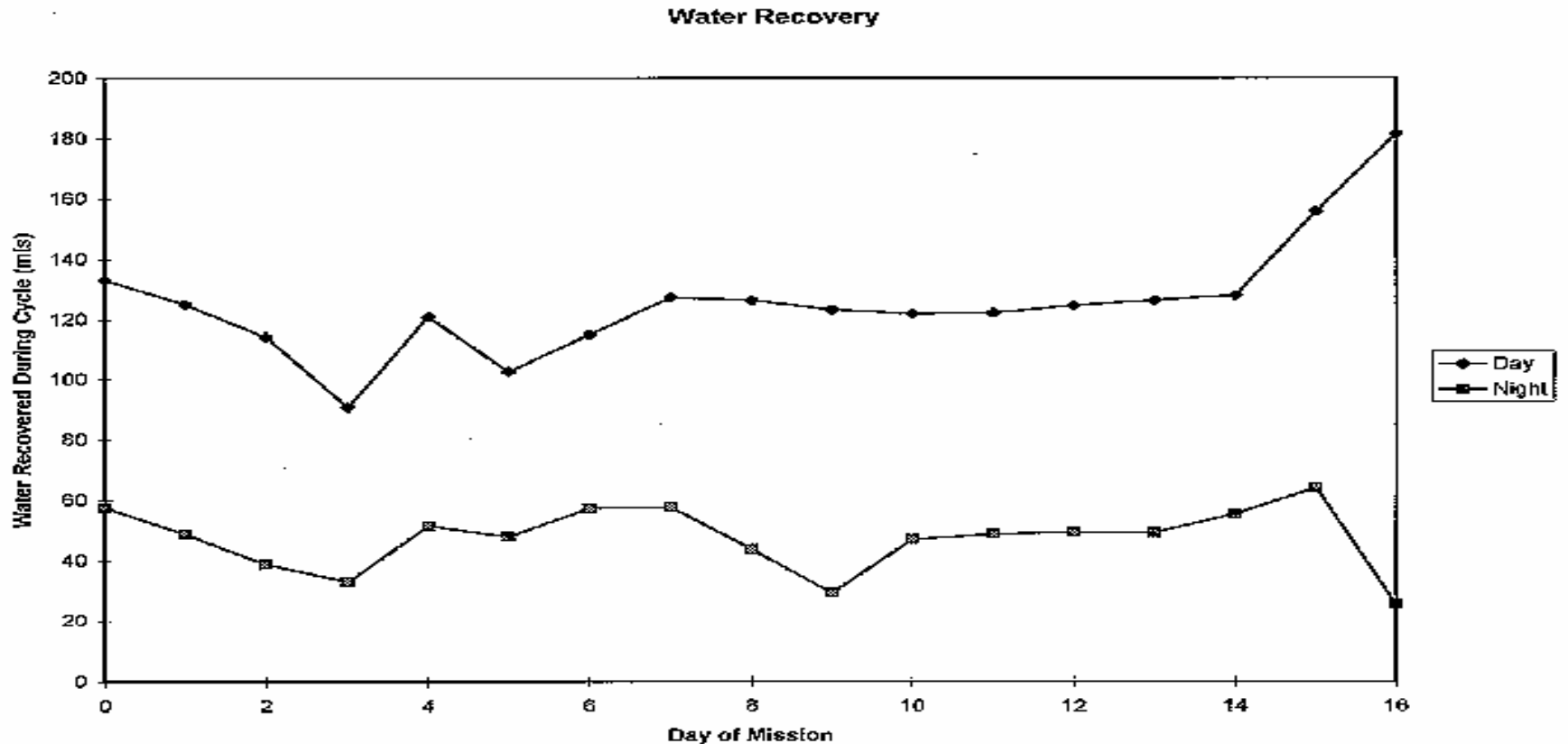
Water Recovery from Air Humidity



Water condensate pumped from humidity control to nutrient delivery:

• 3,000 ml H₂O in 17 days ~ 175 ml/day ≈ 2,350 ml m⁻² day⁻¹

Water Recovery from Air Humidity



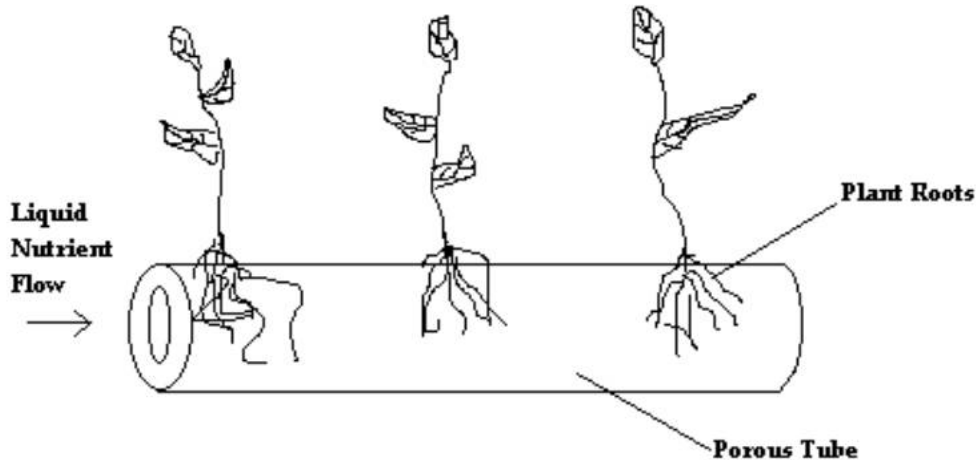
3,000 ml H₂O in 17 days \sim 175 ml/day \approx 2,350 ml m⁻² day⁻¹

Options - Aeroponics

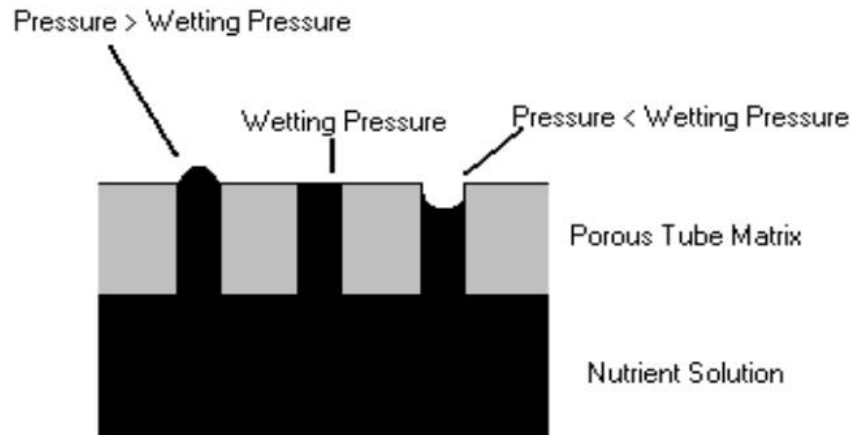


- On Ground:
 - » Good aeration
 - » Low water mass
 - » Low buffer capacity
 - » Good plant performance
- Microgravity:
 - » Challenging

Porous Tube

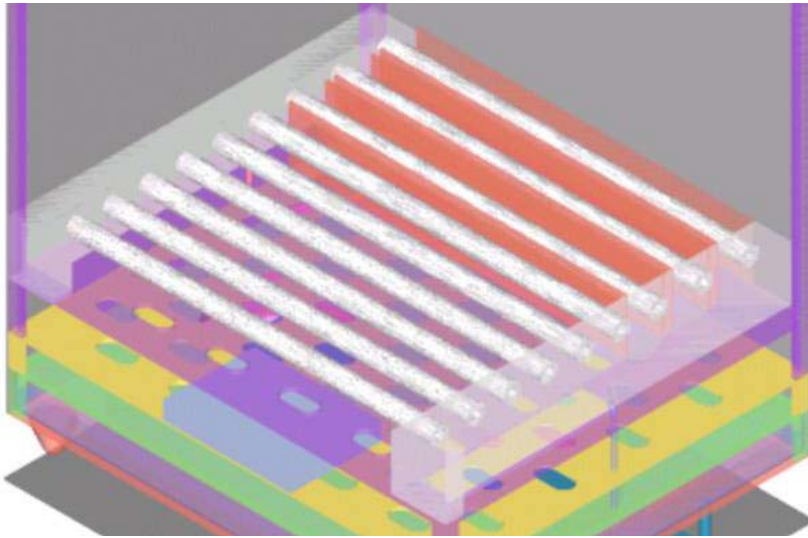


- Surface tension stabilized interface
- Accurate pressure control essential
- Water-availability sensor feed-back difficult
- Used with 'bare' tubes and with 'substrate'

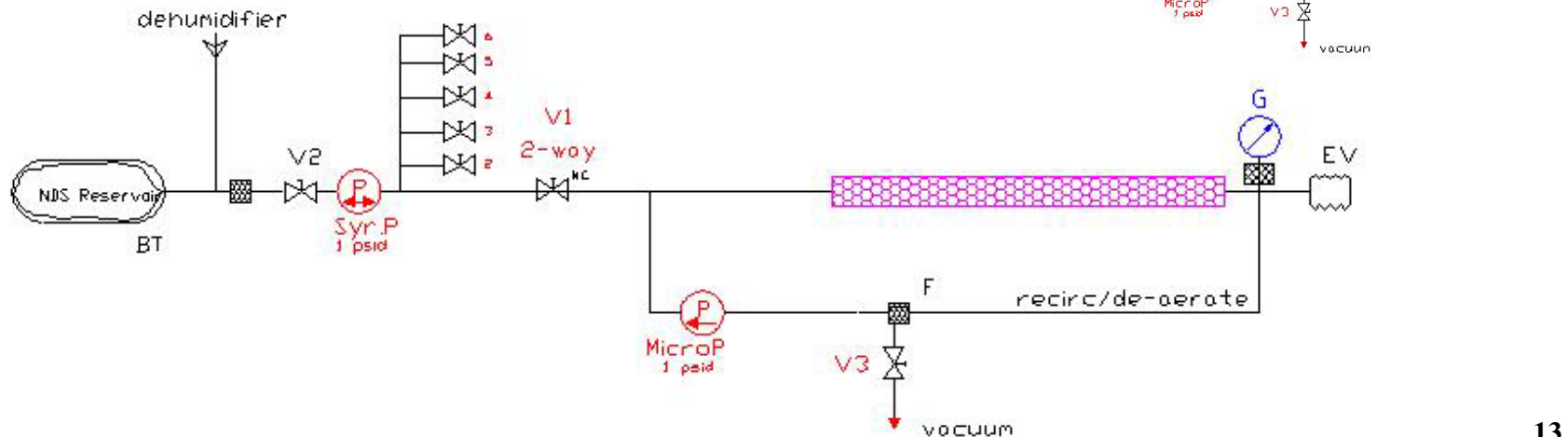


Pore [μm]	Bubble Pressure			Pa	atm
	in HG	in H ₂ O	psi		
0.2	5.60	76.16	2.7507	18971.5	0.18723
0.5	2.60	35.36	1.2771	8808.2	0.08693
1.0	2.35	32.00	1.1558	7971.2	0.07867
2.0	1.60	21.70	0.7838	5405.5	0.05335
5.0	1.21	16.50	0.5959	4110.2	0.04056
10.0	0.68	9.20	0.3323	2291.7	0.02262
20.0	0.40	5.50	0.1986	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

Porous Tube Insert for PGBA

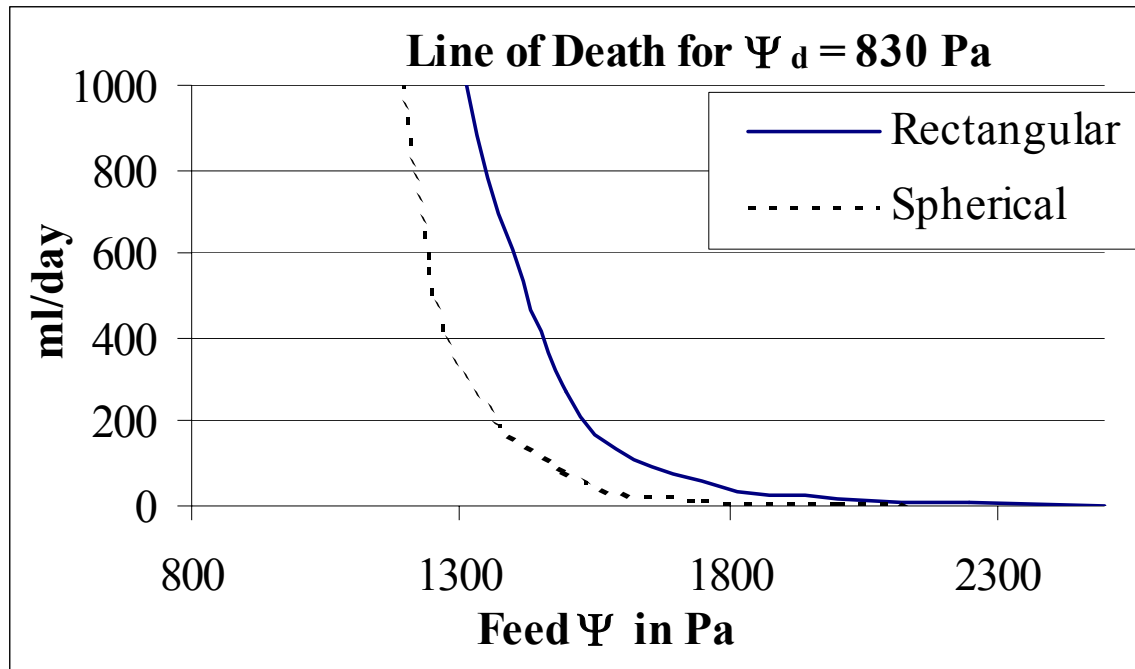


- Side-by-side comparison of matrix and matrix-free systems
- Emphasis on engineering solution
- Demonstrate start-up and growth phases



Pressure Control and Water Flux

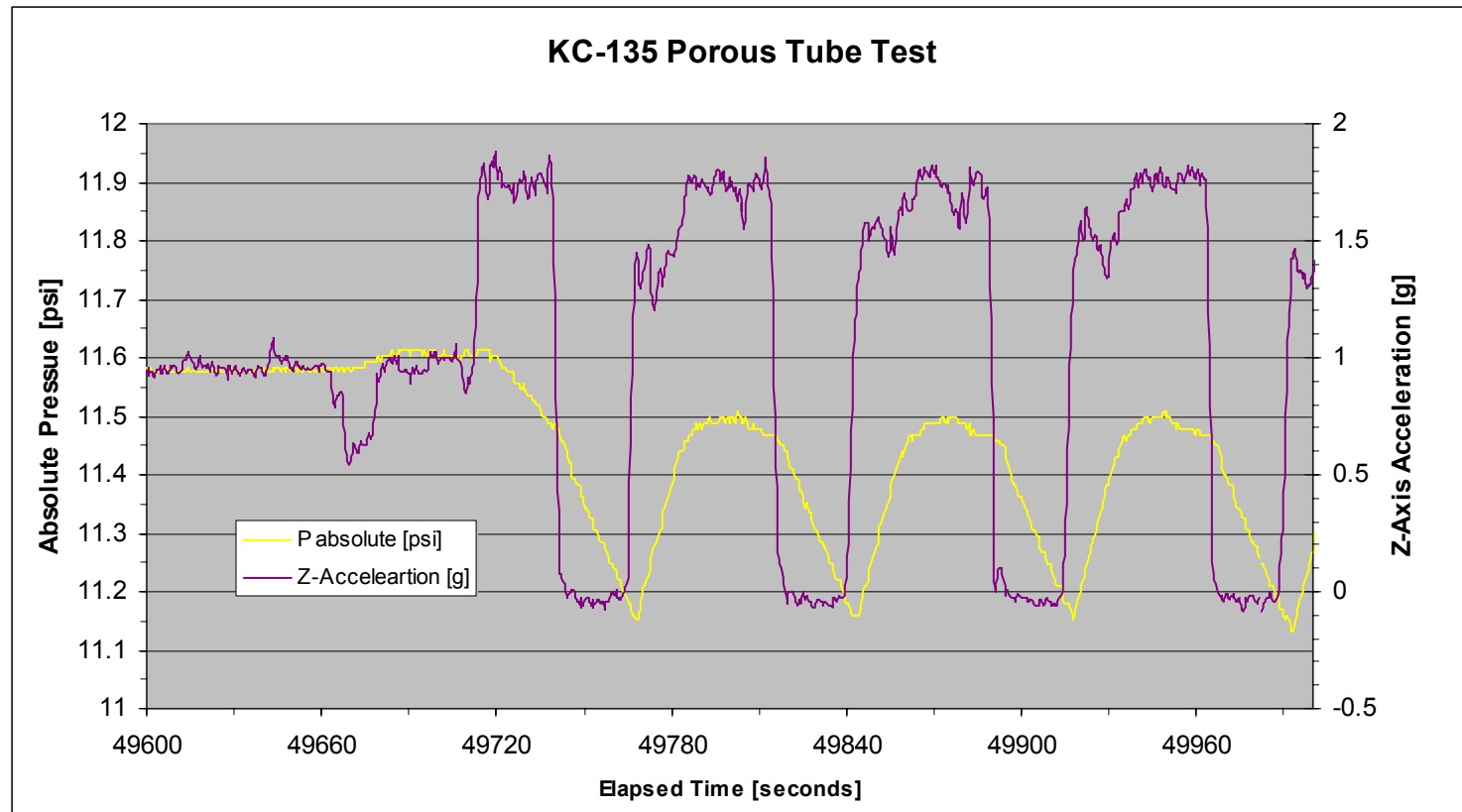
- Water Flow = Backpressure
 - » Suction in porous tube limits max. available water transport rate.



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').

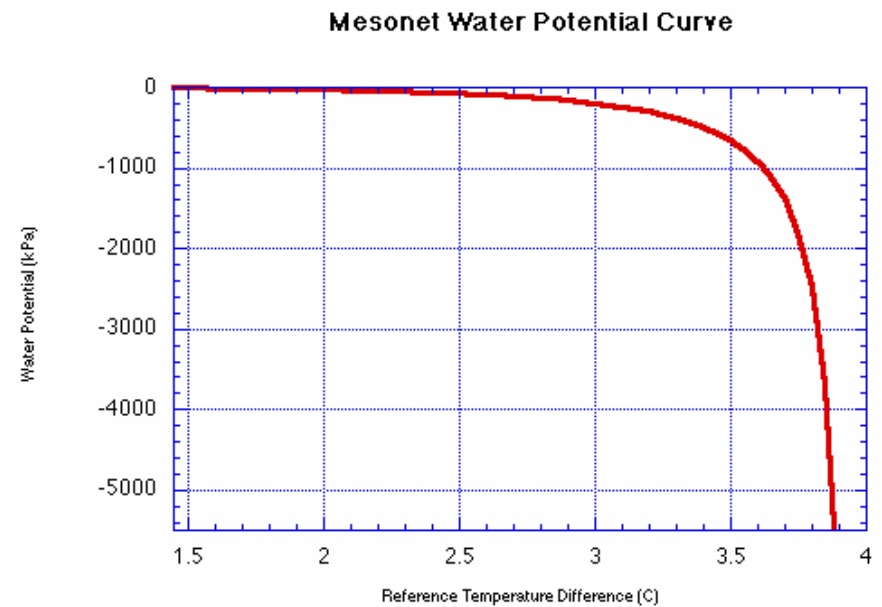
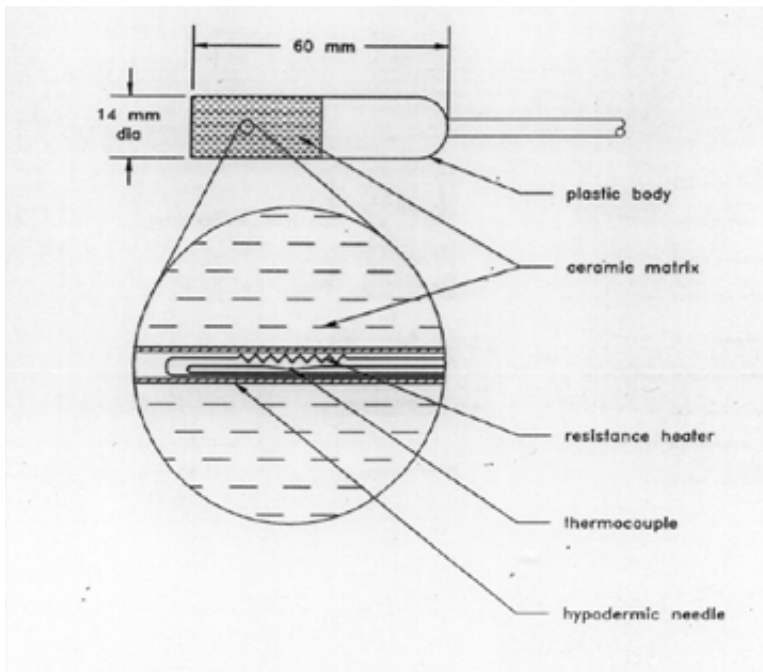
Porous Tube – KC-135 Test

- Cabin pressure fluctuation exceeds control pressure
- Data analysis complicated



Moisture Measurement

- Not Easy



References:

Reece, C. F. 1996: Evaluation of a Line Heat Dissipation Sensor for Measuring Soil Matric Potential. *Soil Sci. Soc. Am. J.* , **60** : 1022-1028

Shaw, B., and L. D. Baver. 1939: Heat conductivity as an index of soil moisture. *J. Am Soc. Agron.* , **31** : 886-889.

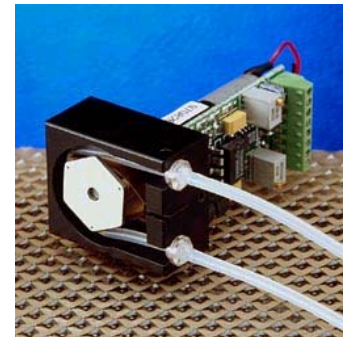
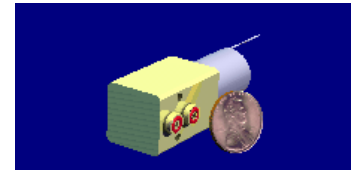
Figure: from <http://parker.ou.edu/~jbasara/2291.html>

Sensor Feedback

- Sensor Options:
 - » Heat capacity of media (heat pulse)
 - » Electric Conductivity
 - » Infrared absorption
 - » Volumetric / mass balance
 - » Surrogate: pressure
- Difficulties:
 - » Calibration and repeatability:
 - Density and heat capacity of media
 - Packing density of matrix
 - Particle size, wicking and wetting characteristics
 - Electric conductivity of nutrient solution
 - Root distribution

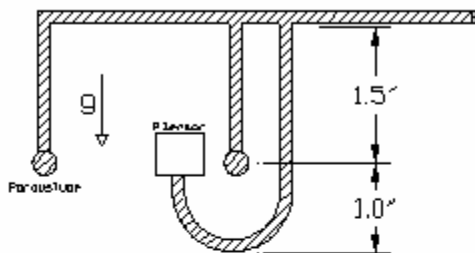
Moisture Control

- Several growth phases to be considered:
 - » Prime system (remove air from supply system)
 - » Imbibe seeds (high water content)
 - » Germinate seeds (reduce water content, good aeration)
 - » Maintain water content / plant individual
 - » Retrieve water prior to harvest
 - » Restart system
- Control Options:
 - » Passive: wetting characteristics / capillary action
 - » Active: Accurate control of small pressure (sensor compatibility)
 - Miniature pumps – small pressure changes / $\mu\text{l}/\text{min}$ flow rate
 - » Active: mass / volume tracking – not feasible for long duration



Small Pressure Control

Evaluated Geometry:



The following pressure sensor geometry is evaluated:

- sensor and tubes in same gravity plane.
- manifold connection above.
- variable size air bubble entrapped.
- Air bubble location varies (liquid shown shaded).

$$\text{Hydrostatic Pressure} = \rho_{H_2O} * g * h,$$

typical desired / optimum: < 250 Pa (<1" H₂O)

$$\text{Capillary Pressure} = \frac{2\sigma}{r} \cong 25 \text{ Pa (0.1" H}_2\text{O)},$$

for: r = Ø6 mm I.D., and σ = 72 dyne/cm.

surface tension induced pressure

due to air bubbles and wetting ≅ 0.5" H₂O,

a)

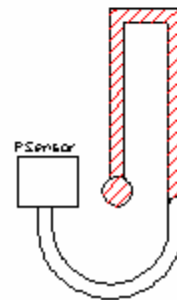
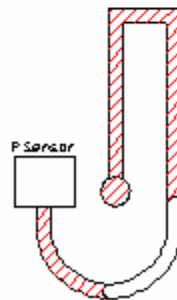
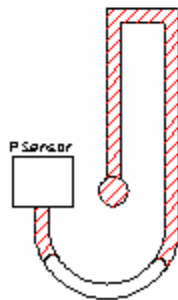
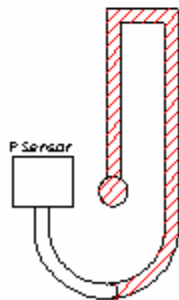
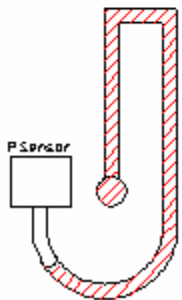
b) PS > PT:
PT too dry
capillary p. effect

c) PS > PT:
PT too WET
capillary p. effect

d) PS ~ PT:
"okay"

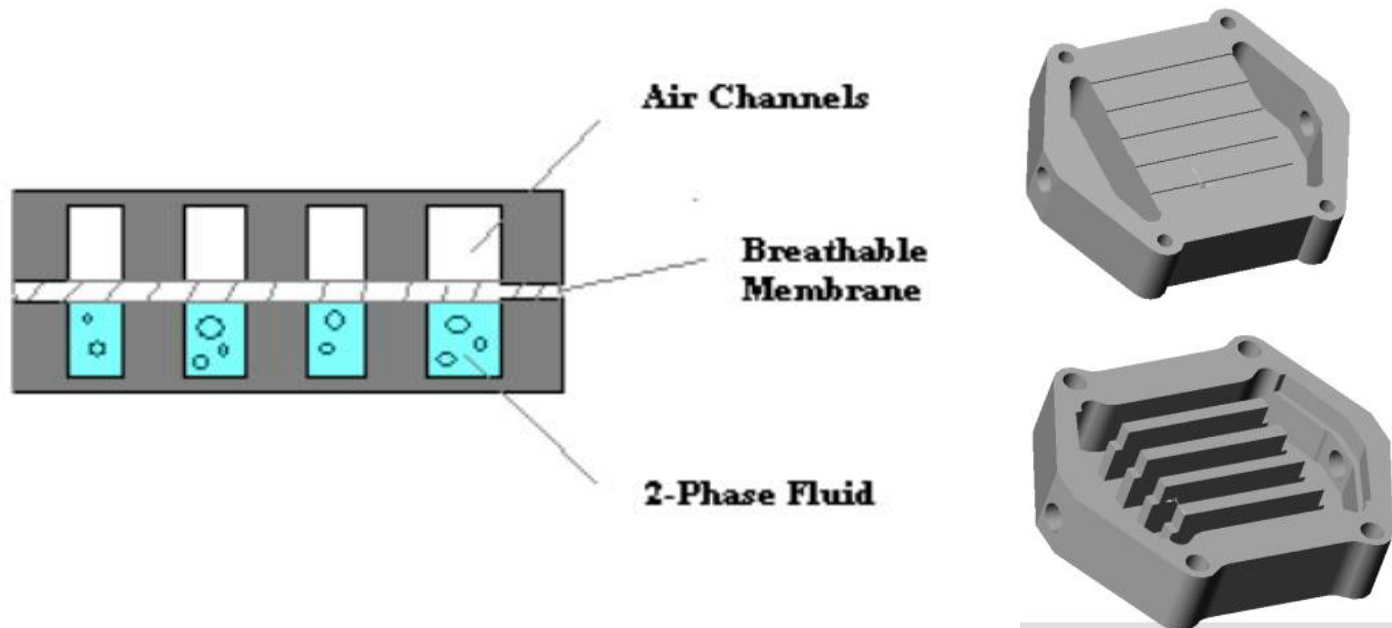
e) PS < PT:
PT too WET

f) PS ~ PT:
"okay"
capillary p. effect



Two-Phase Separation

- Porous media pressure control requires air-free liquid system
 - » Priming (filling with water, removal of entrapped air)
 - » Bubble Trap (de-aerator)



Summary

- Short-term spaceflight with pre-flight priming typically problem-free
- On-orbit startup, and long-term maintenance challenging and risky.
- Unavailability of ideal sensors and actuators for proper control
- Control implementation with error recovery challenging
- Several choices available for science and life support with individual political and performance implications.

Acknowledgements

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