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The Plant Water Management Experiments 5 & 6 on ISS: Hydroponics and Ebb and Flow Archive Report

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Crop production in microgravity may ultimately provide critical whole food nutrition, dietary variety, and psychological benefits to astronauts exploring deep space. Unfortunately, terrestrial plant watering methods face significant challenges when applied aboard spacecraft due to rogue bubbles, ingested gases, ejected droplets, and various unstable liquid interface configurations that arise in microgravity environments. To address these issues, we present the recent results of the Plant Water Management (PWM 5 & 6) technology demonstrations conducted on ISS, where recirculating hydroponic and ebb and flow watering processes are studied using engineered root modules varying solution flow rates, serial and parallel channel flows, channel fill levels, and analog root densities. The microgravity demonstrations employ plumbing elements that exploit the near absence of body forces to achieve passive bubbly flow aeration, bubble separation, gas diversion, bubble mergers and migration, droplet capture, nutrient/water delivery, and the use of plant root geometry for complete microgravity fluid phase separations at different stages of growth. This contractor report provides a draft of subsequent publications, but more importantly at present serves as background information in support of the PWM 5 & 6 video archive uploaded to the NASA PSI website: https://psi.nasa.gov (see Fluid Physics PSI-187).

I. Introduction

PLANT growth habitats aboard spacecraft, moon, and Mars must meet the challenges of routine, robust, and automated water delivery despite the significant reduction in gravitation. Of many watering methods available, NFT Hydroponics and Ebb and Flow methods are pursued herein with a special focus on the microgravity environment. From a spacecraft efficiency point of view, such methods are clean, cleanable, productive, without substrate, automated, provide semi-passive control, and more. However, numerous persistent challenges abound due to the numerous, normally mundane, capillary fluidic phenomena peculiar to the microgravity environment. These include unearthly capillary fluidics over large length scales: (1) unsteady developing transitional multiphase flows, (2) the instability of bubbles, films, rivulets, jets, geysers, and droplets, (3) poor, variable, and hysteretic wetting, (4) pinning, (5) complex metastable free surface geometries, (6) stability of highly parallelized inertial-capillary channels, and (7) practical proof of 'long life cycle' solutions. The presence of gravity in terrestrial plant watering seems to take care of everything without even a second thought from the gardener, who remains in the loop. Our concern here is the unearthly microgravity fluid physics of plant watering aboard spacecraft, which often reduces to the management of low-g bubbles and drops.

In this paper, following a brief overview of PWM Hydroponics, we present a summary of the PWM 5 & 6 technology demonstrations on International Space Station (ISS) during 2024. We provide descriptions of flight hardware, crew procedures, data reduction, and status of the PWM data archive. Preliminary assessments of capillary fluidic device performance are only briefly highlighted for the PWM Open Wedge Test Channels, Gas Diverters, Gas Separators, Water Traps, Aerators, Gas Injectors, and Capillary Reservoirs. More quantitative assessments are expected in a subsequent publication. From a systems engineering perspective, practical concerns associated with long duration operation, aeration targets, test channel lid detail, in-channel germination, and system sanitation are discussed before the contributions of the present work are summarized.

II. PWM-Hydroponics Overview

The Plant Water Management Hydroponics experiment (PWM-Hydroponics, or PWM) is pursued by NASA as a series of low-cost fast-to-flight technology development investigations to demonstrate the feasibility of the general

approach and to advance the readiness level of microgravity hydroponics technologies. Background for the PWM experiments is provided in part in Refs. 1 and 2. In Ref. 3, the ISS PWM-Hydroponics 3 & 4 experiments are reported for 6 8-hour crew days during the March-July 2021 time frame. The central objectives of those demonstrations concerned system priming, start-up, stable single and two-channel parallel flow, impact of single and multiple simple wicking and evapotranspiring plant models varying size and complexity, response to varying fill levels, flow rates, ease of plant insertion and removal, shut down, and more. Specific tests to identify the limits of stable operation as well as the passive mitigation, diversion, and separation of aerating bubbles were reported with over 400 individual tests performed and summarized.

The successful demonstrations of PWM 3 & 4 lead to the advanced Test Channel and Gas Diverter designs of PWM 5 & 6, adding hydroponic and ebb and flow demonstrations with higher fidelity plant root models, cavalier priming, controlled aeration, novel gas separation, water trap and separation, zoomed high-resolution 4K video with 2 FOVs, and more. A raw and reduced video data archive for PWM 5 & 6 is publicly available on the NASA PSI database.[4]

The PWM-Hydroponics hardware is designed for safety and simplicity of use. At the beginning of each operation, the hardware is manually unstowed and assembled on the portable Maintenance Work Area (MWA, i.e., workbench) aboard the ISS. All tests are manually performed by the crew in the open cabin of the ISS, after which the assembly is quickly drained, disassembled and stowed, with all quantitative measures recorded via HD and/or 4K video cameras at 60 fps (e.g., flowrates, fill levels, interface configurations, bubble distributions and velocities, etc.).

III. PWM 5 & 6

NASA authority to proceed on the PWM 5 & 6 technology demonstration began with project kick-off meeting June 29, 2022. Despite the 'Tech Demo' designation, the project addresses numerous applied microgravity fluid physical phenomena rich in practical cross-cutting exploration value beyond plant watering (i.e., fuels, cryogens, coolants, ECLSS fluids, water processing, bio-fluidics, medical fluids, hygiene, habitats, etc.). Thus, the hardware was designed with quantitative measures of rare critical low-g capillary fluidic phenomena in mind. This was to be accomplished employing transparent plumbing elements and digitized HD video data. The hardware was designed, fabricated, flight certified, and delivered October 4, 2023, for launch to ISS November 10, 2023 on SpX-29. Greatly simplifying and speeding the flight qualification process, the decision to employ NutraSweet Fruit Punch as the test fluid was made early. The thermal-fluid and wetting properties are nearly identical to the nutrient solutions used in hydroponics, but Fruit Punch is TOX-0 allowing the experiments to be conducted on the MWA in the open cabin of the ISS. A 48-hour limitation is placed on the wetted experiments due to a potential bio-growth hazard. After 48 hours, the experiments are terminated, and the wetted hardware is 'wet-trashed.'

A. Hardware Overview

Images of PWM set-up on the MWA are provided in Figure 1. Labelled images of the PWM 5 & 6 hardware are provided in Figures 1d and 2. As identified in the figures, the hardware consists of a hydroponic Test Channel (TC), a tubing harness and a peristaltic pump to circulate liquid through the system. The capillary fluidic elements of the TC, Reservoirs (Res), Bubbles Separator (BS), Water Trap (WT) and Bubble Diverter (BD) are 3D printed Formlabs Clear® parts and the 3/16" ID Tygon® tubing is connected using Luer Lock fittings. For PWM-5, two 120 mL syringes are used to prime the system, adjust liquid levels during operations, and make up for liquid lost to evaporation. A 30 mL gas syringe is filled with cabin air and used to inject gas/bubbles into the system during specific tests. The liquid for the tests is an in-flight re-constituted NutraSweet®-based Tropical Fruit Punch prepared by the crew prior to the tests. The thermophysical properties of the beverage are similar to typical plant nutrient solutions with surface tension $\sigma \approx 0.064$ N/m, density $\rho \approx 1010$ kg/m^3, dynamic viscosity $\mu = 0.0012$ kg/m·s, and channel polymer contact angle $\theta \approx 40 \pm 22°$. The variable-speed peristaltic pump provides flow in the range of 0.8-5.1 mL/s (for the 3/16" ID pump head tubing). The pump flow delivery rate is manually adjusted by the crew using the dial on the pump. Precise flowrate values are determined post-flight by calibrating pump head rotation rates with digitally measured occluding bubble velocities and flowrates. All components are mounted to ULTEM™ 3D printed back and base plates, which are then secured to the MWA with hook-and-loop fasteners.

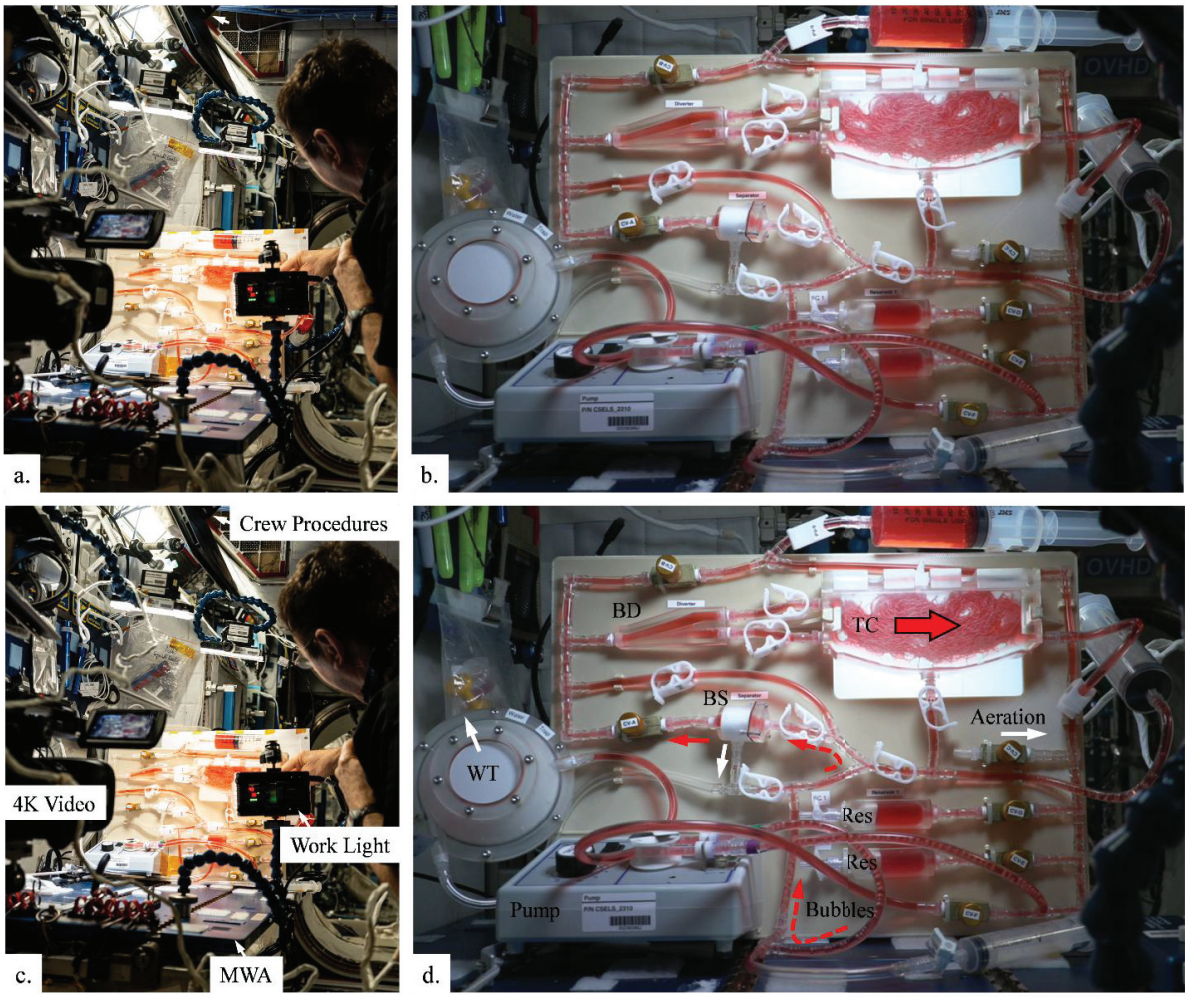


Figure 1. a. Typical over-the-shoulder camera image of Astronaut Michael Barrett conducting PWM-5b on the MWA. b. Image of PWM-5b from primary 4K video cameras during demonstrations of steady Hydroponic Flow with Aeration, Bubble Separation, Water Trap, and Bubble Diversion through the wedge Test Channel (TC) with packed Root R4. Respective labels provided in c. and d. Plant root models R1-R4 are readily removed and replaced.

The hardware may be configured to establish a variety of flow configurations through the plumbing elements and TC during operations. The TC is positioned for distortion-free observation of the flow behavior. In all cases, the TC flow direction is left to right as indicated in Figure 1d and in subsequent figures. Figure 2 provides labeled images of the PWM 5 & 6 flight hardware. Two identical PWM-5 units (5 and 5b) and one PWM-6 unit were shipped to ISS. Each PWM 5 & 6 unit includes at least 10 capillary fluidic devices and at least 14 capillary fluidic fittings. The fluidic devices include TCs, Aerator, Reservoirs, Peristaltic Pump, Air Injection Syringe (AIS), BS, Control Valve (CV), WT, and BD and are designed with passive capillary control in mind. The fluidic fittings are terrestrial COTS items that include the supply drink bag, syringes, fittings (unions, elbows, tees, wyes, expansions, contractions), pinch valves (PV), and control valves that do not consider capillarity in their function. In the presence of capillary two-phase flows, all such plumbing elements play a role in the developing flow regimes. As inadvertent examples, the syringes can serve as bubble generators, simple elbow fittings can shatter bubbly flow regimes, unions can hold-up bubble trains prematurely converting bubbly flows to gas slug flows, and the peristaltic pump can convert regular bubble trains into irregular bubbly flows—a 'froth' at high flow rates.

Solid models of four of the primary capillary devices of PWM 5 & 6 are provided in Figure 3: TC, BD, BS, and WT. Certain characteristic dimensions are included. The differences between PWM-5 (and -5b) and PWM-6 are that PWM-5 (and -5b) employs one TC and two Reservoirs, while PWM-6 employs two TCs and no Reservoirs. PWM-6 pursues the stability of parallel inertial-capillary hydroponic channels as a function of root model. Both PWMs are

capable of dual Hydroponic and E&F demonstrations with targeted performance testing on TC, Aerator, BS, WT, and BD. Each component is first briefly introduced next with further descriptions provided subsequently during discussions of device or system performance. A selection of key system parameters are listed in Table 1.

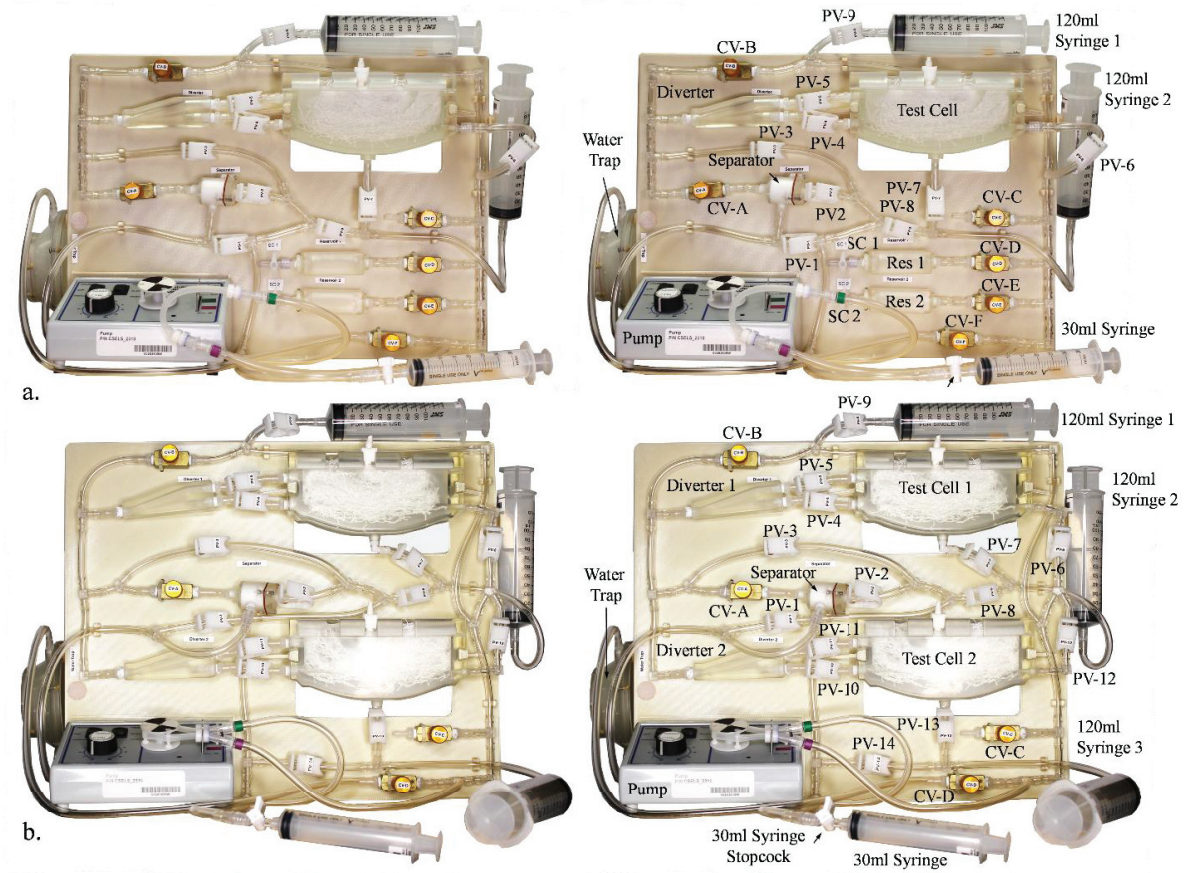
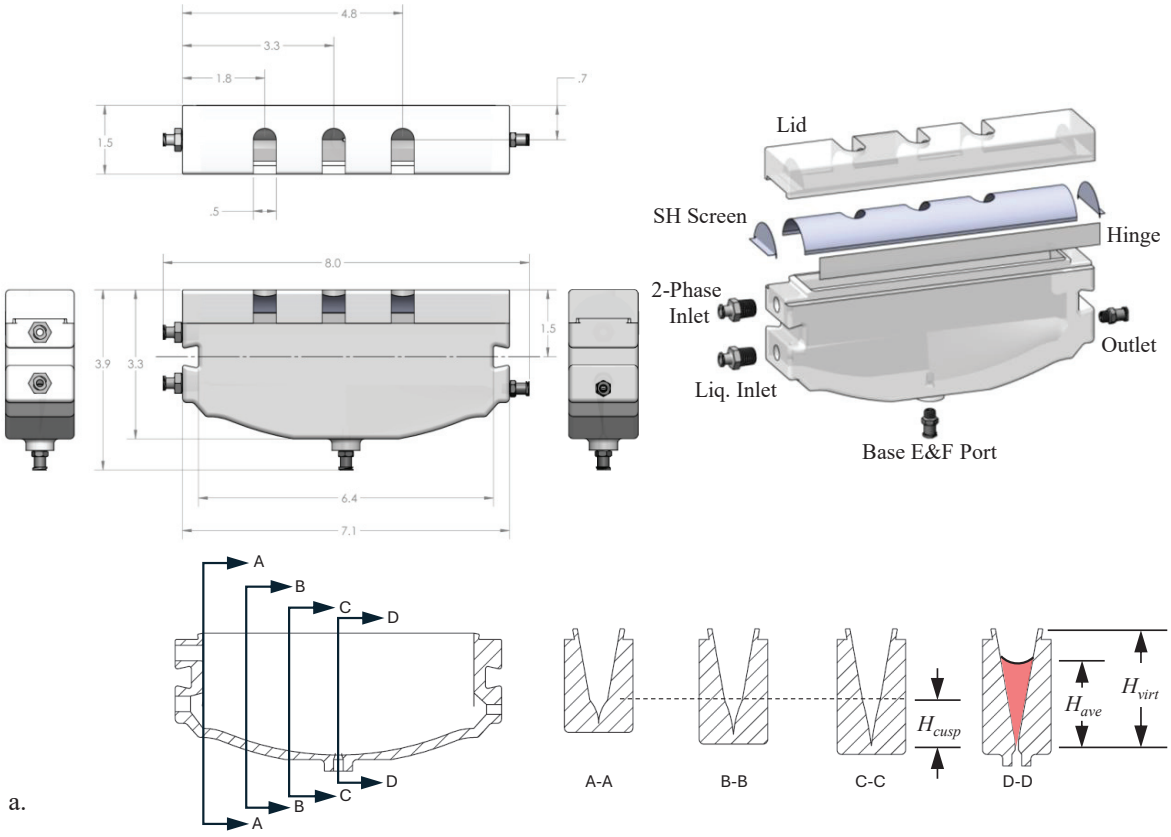


Figure. 2. Images of dry PWM 5 & 6 flight hardware with and without labels for a. PWM-5 (identical to PWM-5b) and b. PWM-6 with Root R4 installed in Test Channel (TC). Here 'Separator' is BS, 'Diverter' is BD, and '30ml Syringe' is the Air Injection Syringe (AIS).


4.8
3.3
1.8
.7
1.5
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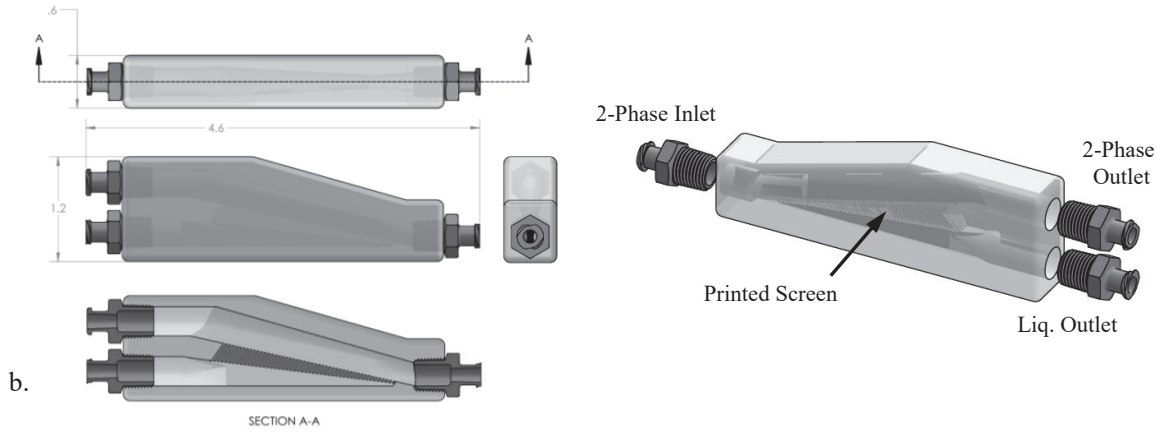
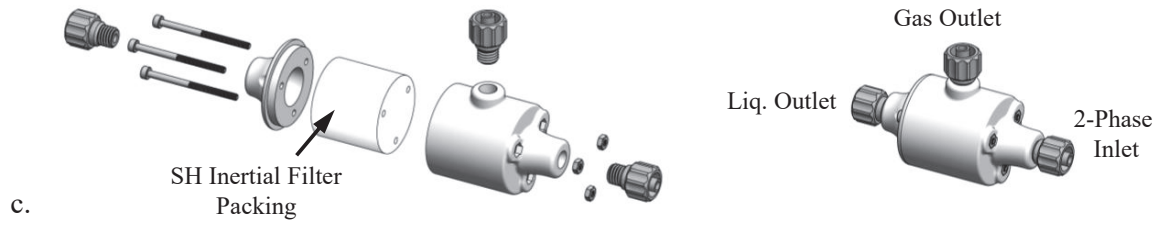
8.0
3.9
3.3
1.5
6.4
7.1
Lid
SH Screen
Hinge
2-Phase Inlet
Outlet
Liq. Inlet
Base E&F Port
A
B
C
D
A-A
B-B
C-C
D-D
H_{cusp}
H_{ave}
H_{virt}

a.


.6
4.6
1.2
SECTION A-A
2-Phase Inlet
2-Phase Outlet
Printed Screen
Liq. Outlet

b.


SH Inertial Filter Packing
Gas Outlet
Liq. Outlet
2-Phase Inlet

c.

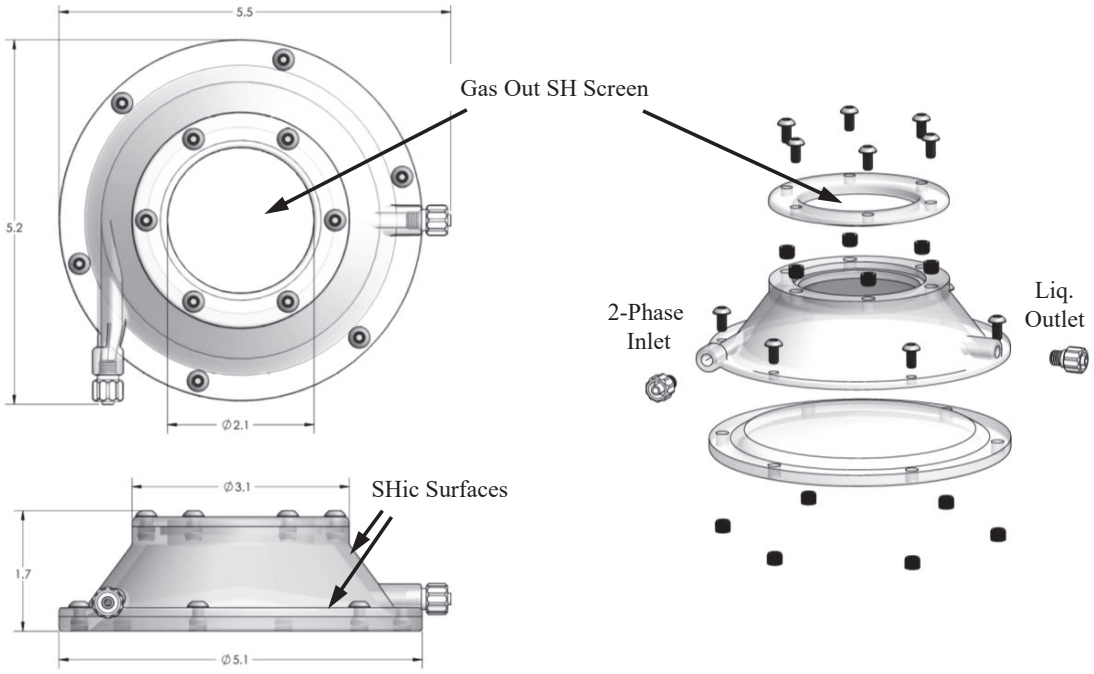


Figure 3. Solid model details of four primary capillary devices of PWM 5 & 6: a. TC, b. BD, c. BS, and d. WT. (Dimensions in inches)

Table 1. TC and Tubing Harness data.

Test Cell		Tubing Harness	
Length	15 cm	Inner Diameter	3/16 inch
Included Angle	20º	Upstream Length	116 cm
Effective Height	6 cm	Downstream Length	81 cm
Volume	113 mL	Total Length	197 cm
		Volume	35 mL

Test Channel (TC). Test Channel perspectives with dimensions are provided in Figure 3a. The ≈ 6 cm high, 16.25 cm long TC is a 20° (α = 10°) included angle open wedge channel with centered tapered cusp drain at its base, continuous 90° pinning edge, and superhydrophobic (SH) living hinge lid with 3 ports for plants. The TC holds 113 mL when filled flush to the pinning edge. The lower inlet for the TC is aligned with the cusp and the upper inlet is 27 mm higher. The non-wetting inner lid surface is a SH-PTFE monolithic screen (not a coating) with hopes to rebound ejected droplets at the entrance of the TC and allow for their translucent visualization. The effectiveness of this approach will be discussed herein. The lid is secured with clear tape serving as a living hinge for ease of plant placement and removal. The TC is SLA printed of flight certified Formlabs Clear® Resin. Upper and lower inlets are used, but only a single lower outlet. As previously demonstrated on ISS,[5] and building upon enhancements from the Space Cup Patent,[6] the wedge geometry provides a measure of spontaneous bubble-free priming and excellent stability for flow along the wedge with the passive capability to drive bubbles toward the free surface where they merge and leave the flow. Thus, the TC provides a measure of passive bubble separation for the system. This mechanism is promoted further by the presence of plant roots which trap bubbles, enhancing mergers, and driving them out of the channel with increased efficiency. The TC dimensions balance the desire for large fluid volume and elevated flow rates (up to 10 mL/s) with adequate stability to crew induced perturbations (~ $10^{-2}g_o$) resisted by hysteretic and/or pinned contact lines due to the partial wetting conditions of the polymer-Fruit Punch system with contact angles $30° < \theta < 80°$. The presence of plant roots enhances liquid stability by reducing characteristic free surface dimensions and increasing viscous damping. For dense root packings, the TC can serve as a perfect passive bubble separator (i.e., R4), as will be demonstrated.

Bubble Diverter (BD). The BD is perhaps best described as a gas diverter[7] (Fig. 3b), with the primary purpose of delivering 100% liquid to the TC lower inlet, diverting all gas/bubbles into the upper TC inlet. The device splits the incoming flow into single phase liquid flow into the lower TC inlet, while a higher gas concentration two-phase flow

is directed into the upper TC inlet. The TC inlets establish similar downstream pressures, and the bubble separation mechanism is managed by a bubble point-limited sorting mechanism of the integrated diverter screen and inlet bubble diameter distribution. For bubble diameters < δ_{BD} and device pressure drop $\Delta P_{BD} < P_{\delta BP}$, 100% liquid enters the lower TC inlet port. The increased density of bubbles directed into the upper TC inlet port merge quickly and are driven by the open wedge TC geometry to the free surface where the majority escape the channel flow reducing the need for the channel to separate the bubbles all along its length. Providing predominately liquid flow through the lower TC inlet reduces the potentially negative impacts of bubbles deep within the plant roots which tend to lift the roots out of channel.[3] The BD can divert a variety of two-phase flow regimes such as sparse bubble, bubbly, bubble slug, and gas slug flows). The BD is currently TRL 8 with devices employed in cross-cutting applications aboard ISS (i.e., a urine pretreatment concentration measurement plumbing element where only liquid is to be sampled from a sparse bubble two-phase flow).

Bubble Separator (BS). The BS is more specifically described as a Superhydrophobic Multiplexed Inertial Filter, Figure 3c. The Multiplexed Inertial Filter was first patented for low-g droplet/mist capture applications aboard spacecraft[8] but is reformatted for PWM using SH materials to achieve 100% bubble separations from aqueous solutions.[9] Not shown in Figure 3c, the BS employs numerous parallel SH helical passages to centrifuge and adhere bubbles to the porous packing allowing the locally pressurized gas to escape the otherwise uninterrupted liquid flow in contrast to other membrane methods[10] and microfluidic bubble trap products. Complete phase separations are possible with such an easily deployed in-line device and the potential benefits to cross-cutting de-bubbling liquids in space are compelling.

Water Trap (WT). More appropriately described as a low-g Capillary Coalescing Filter in Figure 3d, the WT is employed with PWM as a redundant device to assure that no liquid escapes from the BS gas outlet line into the ISS cabin. During BS limit tests it was desired to push the BS beyond the limit of liquid escape through the gas outlet line. Such widely varying liquid content two-phase flow is captured and held by the superhydrophilic (SHic) circular circumferential interior corner of the WT (conical sidewalls and base), while allowing bubbles to escape into the core and out of the WT through a central circular SH-PTFE screen. The interior corner of the device performs a similar bubble separating function as the open wedge TC, but with improved performance due to the perfectly wetting SHic Rayon-lined walls of the WT wedge and slight centrifugal forces generated by the circumferential inlet and flow. The WT approach is patent pending[11] and has found cross-cutting applications (i.e., primary separation function of a spacecraft wet vac[12]). The WT functions as a passive phase separator or a water trap depending on whether the liquid is or is not drained during operation.

Aerator. The aerator consists of a simple Tee fitting through CV-C just downstream of the TC on the low-pressure side of the loop as shown in Figure 1. More elaborate capillary venturi aerators were originally designed and built for this function, but the simple COTS Tee junction performs adequately, and for such a small form factor. The sensitive control valve CV-C (1/8" Deltrol Needle Valve, EN10B) allows the crew to precisely regulate the air flowrate into the loop. The added degree of freedom of flowrate adjustments at the pump establishes a wide variety of aerating two-phase flows. The highly regular (bubble) two-phase flow regimes generated at the aerator are often disorganized downstream due to numerous fittings and the pump as will be shown. The capability of generating aerating bubbles and then safely removing them essentially eliminates concerns of historically hypoxic water supplies aboard spacecraft. Because the pump volumetric flowrate Q_{pump} is known and the gas flowrate Q_g may be measured from the video data, the liquid flowrate may be found from $Q_l = Q_{pump} - Q_g$, from which the flowrate ratio may be found, $\phi = Q_g/Q_l$. For occluding flows, for fixed Q_{pump}, increasing the aeration rate does not change the liquid velocity, but reduces the liquid flowrate, increasing the flowrate ratio. We note that increasing aeration decreases liquid superficial velocity ($= Q_l/A_{tube}$). The naming scheme for the CV-C valve position is described below:

The Deltrol Fluid Products 1/8" Easy Read control valves employed for PWM 5 & 6 for aeration (CV-C) and pressure control (CV-A) are quantified by number of turns of the valve stem determined visually by colored rings on the base of the control dial and a linear 0 to 9 number scale around the outside of the dial as observed in the figure below. When the valve is fully closed, no colors are visible at the base of the dial and the dial's scale reads 1. When the valve is fully open, as shown in the figure below, five color bands are visible and the dial scale reads 5. The notation for different dial settings is shown in the Valve Table below. Note that the colored bands become partially visible before the control valve is assigned a color. For instance, a small portion of the red band becomes visible around N5, but the valve is not considered "red" until the red band is fully visible at R0.

CV-C Valve Stem: Fully open Deltrol CV revealing five colored bands and control dial tick marks: color bands red, blue, orange, green, and white. (Note that at this fully opened condition the internal structure of the valve stem is visible just right of the white color band.)

Valve Table. Range of dial settings for PWM's Deltrol CVs: color bands red (R), blue (B), orange (O), green (G), white (W), and internal structure (I).

Fully Closed	No colors showing	0 or N1
Partially Open		N2
		N3
		N4
		N5
		N6
		N7
		N8
		N9
	Red Band fully visible	R0
		R1 – R8
		R9
	Blue Band fully visible	B0
		B1 – B9
	Orange Band fully visible	O0 – O9
	Green Band fully visible	G0 – G9
	White Band fully visible	W0 – W9
	Internal Structure showing	I0 – I4
Fully Open		1 or I5

Reservoirs (PWM-5 and -5b). Dual reservoirs with 2 cm inner diameter, 4 cm barrel length, and nominal 15 mL capacity are connected to the suction side of the loop just upstream of the Pump for the PWM-5 and identical PWM-5b hardware as shown in Figure 2a. The two reservoirs emulate plant nutrient solution and water supply. By opening the Reservoir breather stopcocks (SC), adjusting the Reservoir control valves CV-D and CV-E determines the routine steady passive injection of simulated 'nutrient solution' and 'water supply.' Demonstrations of this straightforward capability varying serial and simultaneous injection rates and volumes are performed. Automation of the process is a natural direction for the development of the simple approach.

Syringes. The 120 mL Syringes are filled directly from the onboard ISS Fruit Punch drink bags. They are then connected to the PWM 5 & 6 conduit and employed to prime the system, adjust TC Hydroponic flow fill levels, conduct E&F tests, and drain the system. The process of filling a drink bag from the ISS PWD ingests a small amount of air from the drink bag cannula into the bag. The process of transferring liquid from the drink bag to the syringes often introduces more gas. Crew time is saved by treating these steps cavalierly and lastly applying centrifugal accelerations to the 120 mL Syringes before bleeding gas out of them and connecting them to the loop. It is then possible to conduct bubble-free syringe primes and drains of the PWM TCs and loop with a concerted effort not to exceed the ingestion limits (velocities) of the in and out flow of liquid from the syringes. But such manually controlled flows require continued concentration from the crew and continued patience from the science team on the ground. Because the PWM 5 & 6 hardware contains redundant passive bubble separating devices, recovery from any

inadvertent bubble ingestion is automatic. The impact of this 'feature' of the PWM hardware subconsciously acts on the science team to relax concerns about bubbles in the syringes and loop and press ahead with faster more cavalier syringe fills and drains without centrifuging and bleeding air from the syringes of the loop. It was routinely heard in the control room that 'we can determine the liquid content in the bubble-filled 120 mL Syringes by optically measuring the gas contents post-flight.' Unfortunately, this is not always possible.

The 30 mL Syringes (Air Injection Syringe, AIS) attach to the positive pressure side of the loop just downstream of the pump. Using these air-filled syringes, highly regulated bubbly flows and bubble trains may be manually injected into the loop without being churned by the peristaltic pump. In such cases, the pump flowrate is the liquid flowrate, and the gas syringe injection rate is the gas flowrate. Thus, $Q_{tot} = Q_{ginj} + Q_{pump}$ and $\phi = Q_{ginj}/Q_{pump}$. For occluding flows, the liquid velocity increases with air injection, but the liquid flowrate and superficial velocity remain constant. A two-way stopcock attached to the 30 mL Syringe allows for various 'clean' bubble injections serving as a second aerator. However, at high pump speeds, fittings downstream of the gas injection location still managed to disrupt the clean bubble flow regime injected.

Modes of Operation. The somewhat entangled plumbing of the PWM Hydroponic hardware enables the variety of loop functions necessary to meet the technology development requirements of the investigation. The ≥ 5 modes of the PWM 5 & 6 hardware operation are sketched in Figure 4. Replacement of all four root models is assumed as well as Hydroponic tests with no root models. Duplicate circuits are not shown for PWM-6. Modes with Reservoirs engaged are not shown. The loops include (1) E&F operations from 120 mL Syringes 1 and 2 through TC base, lower inlet, and outlet (ref. Fig. 4a-b), (2) Hydroponic flow with and without Aeration, Gas Injection, and Bubble Diversion (ref. Fig. 4c), (3) Hydroponic flow with and without Aeration, Gas Injection, Bubble Separation, Water Trap, and Bubble Diversion (ref. Fig. 4d), (4) Water Trap as a variable volume liquid trap and bubble separator (ref. Fig. 4e), and (5) Parallel Hydroponic flow with and without Aeration, Gas Injection, Bubble Separation, Water Trap, and Bubble Diversion (ref. Fig. 4f). The solid red lines symbolize single-phase liquid flow, and the dashed lines symbolize two-phase flow. The latter consists generally of gas slug, bubble trains, or bubbly two-phase flows. Flow regimes are established and reported herein where 100% gas and liquid separations are observed. Other PWM 5 & 6 operational modes can be achieved but were not pursued.

B. Root Models

Early ground tests performed using a variety of plants (i.e., peppers, arugula, etc.) grown in PWM Hydroponic channels were pursued to observe plant root behavior during maturation. (Natural roots were originally proposed for the flight tests but tended to disintegrate when dried.) Results such as depicted in Figure 5 were used to guide the development of the four polyester root models shown in Figure 6. Root model data is listed in Table 2. The multiply cold water rinsed root models mimic the root diameter, length, wettability, and density of the sparse and packed natural roots observed during the terrestrial growth experiments. By touch, root stiffnesses also appeared similar between the wetted synthetic and natural pepper roots. As shown in Figure 7a, the synthetic roots consist of single strands of 100% polyester Coats & Clark Inc. Red Heart® Scrubby Yarn (Coconut, Gauge: 4–Medium). The roots of the root models are constructed as depicted Figure 7, with the double-stranded roots separated into single strands, laid out lengthwise and centered, bundled and tied at their center, folded and drawn through a 25.4 mm length of polyolefin heat shrink, and trimmed. The heat shrink is then heated for a tight fit while serving as the partially wettable plant 'stem'. An approximately 15 mm by 13 mm by 8 mm wedge of poorly wetting closed cell nylon foam is punched for a press fit around the heat shrink stem, as shown completed in Figures 6 and 7g. The foam wedges of the root models slide easily into the slots of the TC lid identified in Figure 3a.

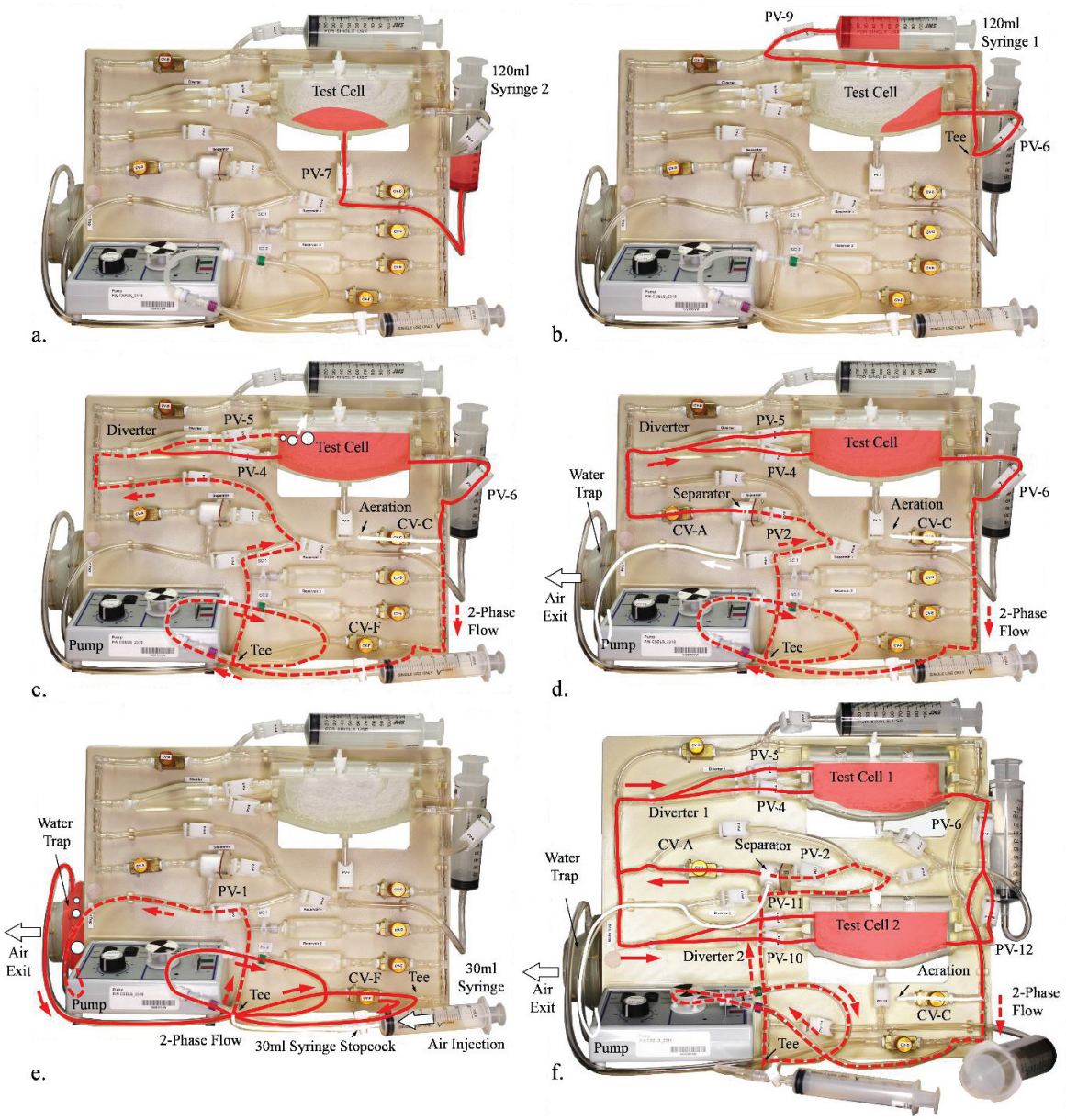


Figure 4. Selection of PWM 5 & 6 modes of operation: PWM-5 E&F operations from 120 mL Syringes through a. TC base and b. TC lower outlet, PWM-5 (and -5b) single channel Hydroponic flow with c. Aeration and Bubble Diversion, d. with Aeration, Bubble Separation, Water Trap, and Bubble Diversion, e. with PWM-5 Water Trap with Air Injection and Separation, and f. PWM-6 Parallel Hydroponic flow with Aeration, Bubble Separation, Water Trap, and Bubble Diversion.

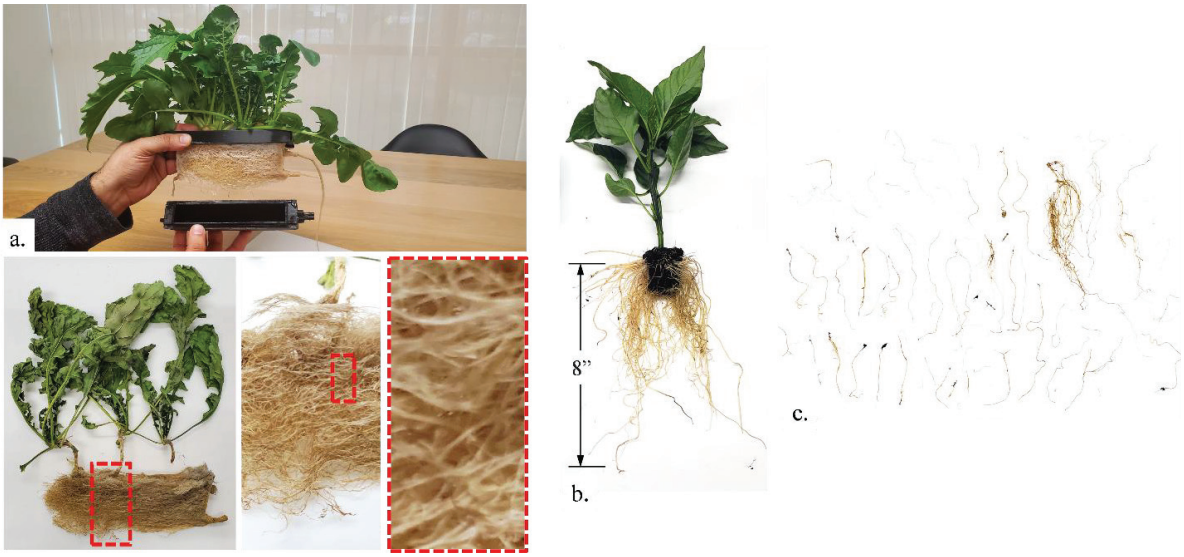


Figure 5. Early hydroponic ground growth tests using the PWM Hydroponic TC to aid selection of synthetic root models: a. Approximately 40-day Arugula extracted from TC with magnified root zone images. b. 45-day Pepper root zone removed from TC and c. dissected to record root diameters, lengths, and length distribution.

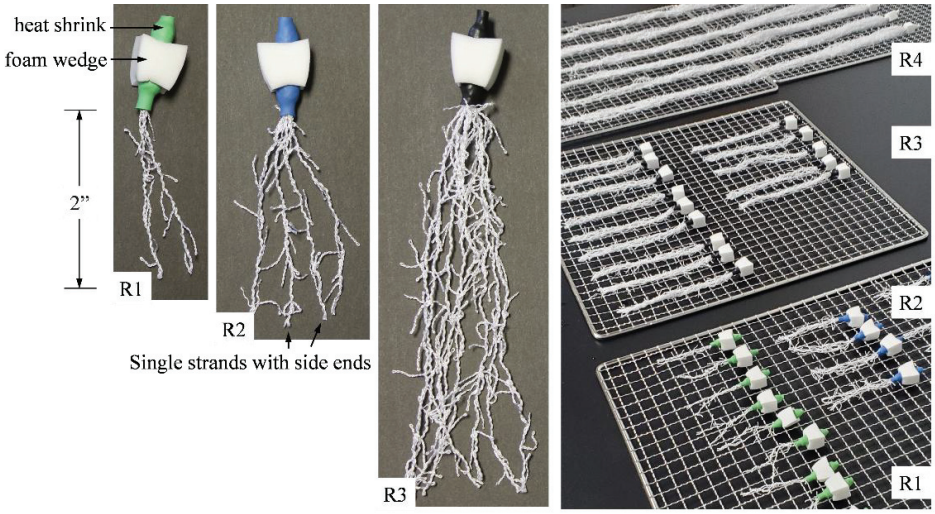


Figure 6. Labelled images of synthetic flight root models R1, R2, R3, and R4, intending to model sparse and packed root limits (ref. Table 1).

Table 2. Synthetic root model data: As shown in Figure 6, single primary strand diameter is 100 µm, single secondary dead end strand diameter is 458 µm, and each single stand consists of dozens of ~ 100 µm diameter fibers. The single strand root volume and mass per length are 0.382 ± < 8 % mL/m and 0.558 g/m ± < 2 %, as determined by submersion and dry mass tests, respectively. The fiber bundles are perfectly wetted by the Fruit Punch test liquid. The density of the individual polyester fibers was measured to be 1.56 g/mL.

Root (R#)	Op. Nom.	Color	#Roots (#/TC)	#Roots/Root Length (#/inch)	#Roots/Root Length (#/inch)	Tot. Root Length (m)	Root Vol. (mL)
R1	sparse	green	3	2/2”	-	0.10	0.1
R2	small	blue	3	4/5”	-	0.25	0.3
R3	medium	black	3	8/5”	-	1.02	1.2
R3	dense	white	1	10/6”	20/24”	13.72	5.2

*Note that ‘R0’ is employed to denote comparative TC flows with no root models installed

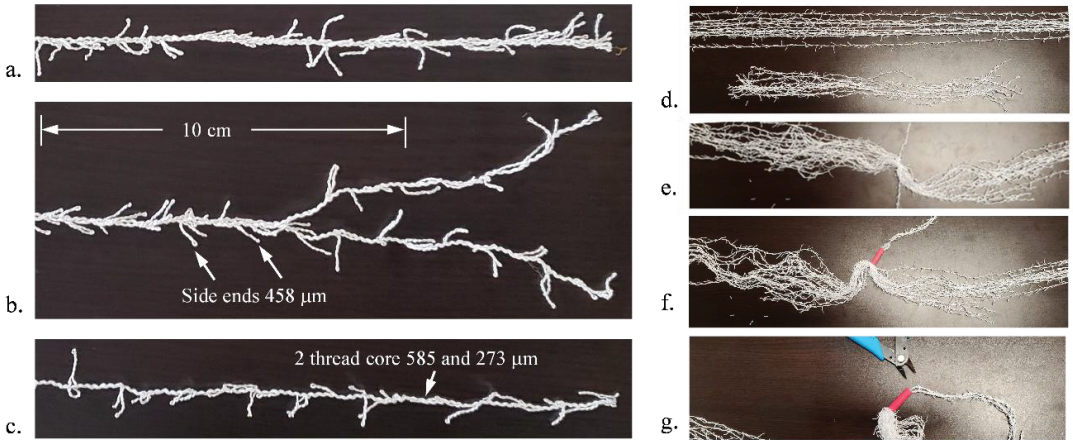


Figure 7. Synthetic roots and assembly. a. As purchased: double-wound strand, b. split, and c. as employed as single strand (ODs labelled). Root model R4 assembly: d. layout, e. center, overlay and tie off, f. draw through polyolefin heat shrink, and g. cut to finish.

IV. Summary of Flight Operations on ISS

Flight operations for the PWM 5 & 6 Hydroponics demonstrations were conducted by eight crew members in three test series: January 16-17, July 16-17, and October 10-11 of 2021. Due to the possibility of microbial growth, current ISS safety protocols require the trashing of all wetted components after 48 hours exposure. This requirement guided the decisions on the order of tests performed. ISS flight operations are only summarized herein. Each of the three operations included a hardware setup, system prime, experiment operations, teardown, and stow activity. During system prime and experiment operations, the investigator team had direct audio communication with the crew and real-time downlink video from one or two Sony Camcorders with 1280x720 pixel HD resolution at either 30 or 60 fps and/or 3840x2160 pixel 4K resolution at 60 fps. The crew also took occasional still images throughout the demonstrations using a Nikon D5 DSLR camera. The crew downlinked the locally recorded video and still images to the ground after each operation.

The chronological order of ISS flight operations is PWM-5, PWM-6, and PWM-5b as listed in Table 3 using NASA timekeeping format GMT:ddd:hhh:mm:ss for the 2024 calendar year unless otherwise specified. Abbreviated 'as-planned' summaries of accomplishments from the crew procedures are listed below in approximate chronological order as conducted on ISS. Notes regarding deviations and excursions from the nominal plan are provided including extra science activities when significant. The complete set of PWM-5 (identical to PWM-5b) and PWM-6 Crew Procedures are provided in Appendix C. The true timeline of tests and procedures conducted requires a query of the PWM-5, -5b, and -6 video (with audio) data archive. The archives are available digitally separately.

Table 3. Nominal PWM 5 & 6 Flight Operations GMT Chronology completed during 2024 calendar year. Note that hardware set-up was normally proceeded by a 10-20 min space-to-ground crew conference call. All science team space-to-ground communication was performed by co-author L. Torres.

Tech. Demo	Crew	Day 0/1 ddd:hr	Day 2 ddd:hr	Day 3 ddd:hr	Primary Objectives
PWM-5	Moghbeli Furukawa Mogensen	15:01:30	16:08:30	17:08:30	R1-R4: E&F, Single Channel TC Hydroponic flow with and without Aeration, BS, WT, BD, and AIS Long duration Hydroponic low runs
PWM-6	Williams Wilmore	177:1:30	178:8:30	179:8:45	R1-R4: E&F, Parallel Channel TC Hydroponic flow with and without Aeration, BS, WT, and BD
PWM-5b	Barratt Benedikt Epps	283:10:30	284:8:20	-	R0-R4: E&F, Single Channel TC Hydroponic flow with focus on high resolution Aeration, BS, WT, and BD with access to 2 science cameras

Table 4. Summary of 2024 PWM 5 & 6 Hydroponics operations.

GMT Day	Date (mm/dd)	Channel (W/C)	Select Demonstrations	Crew Time (hh:mm)
16	1/16	PWM-5	R4, E&F, Hydroponics, Aeration, AIS Gas Injection, BS, WT, BD	8:30
17	1/17	PWM-5	R1, R2, R3, E&F, Steady Hydroponics Aeration, AIS, BS, WT, BD, Reservoirs	8:30
178	7/16	PWM-6	R4, E&F, Parallel Hydroponics, Aeration, AIS, BS, WT, BD	8:30
179	7/17	PWM-6	R1, R2, R3, E&F, Parallel Hydroponics, Aeration, AIS, BS, WT, BD	8:45
283	10/10	PWM-5b	R4, E&F, Hydroponics, Aeration, AIS, BS, WT, BD, Magnified FOV	10:30*
284	10/11	PWM-5b	R1, R2, R3, R0, E&F, Hydroponics, Aeration, AIS, BS, WT, BD, Magnified FOV	8:20

**Includes setup*

PWM-5 Performance Summary

The PWM-5 operations sought to demonstrate design advances for all aspects of the PWM-3 and PWM-4 hardware performance including improved TC, TC pinning, TC SH lid, larger volume TC, new E&F capability, new improved BD, new BS and WT, improved root model variability and fidelity, 4K camera resolution, and more. Numerous 'long duration' runs establishing elevated TRL using these components were also important objectives. Planned procedure details for PWM-5 are listed below with cryptic commentary on outcome and/or deviations that actually occurred in italic. We note that by '100% separation' we imply 'to the best of our image quality'—lighting, camera settings, camera resolution, and frame rate, including timely crew observations and commentary.

PWM-5 ISS Astronaut Crew: NASA Jasmin Moghbeli, JAXA Satoshi Furukawa, and ESA Andreas Morgensen
Day 0, GMT2024:15, January 15, 2024: 20 min PWM conference between the ground team and ISS crew
Day 1, GMT2024:16, January 16, 2024: Unstow and Set-up
Day 2, GMT2024:17, January 17, 2024: Prime and Science Operations
Day 3, GMT2024:18, January 18, 2024: Science Operations

PWM-5 Crew Procedure Details: Planned (estimated time 08:10)
Day 0/1: (01:30)
1. Crew Conference call
2. Hardware gather/unstow
3. Hardware set-up on MWA

Day 2: (08:30) Root Model R4 in TC
1. Reconstitute PWM-provided Fruit Punch drink bag, 1ea 250 mL. Prime 120mL Syringes 1 and 2, tubing, Reservoirs, and TC (01:00)
2. Dry TC Prime (00:10)
3. E&F from TC Base tests (no pump) (00:30)
4. E&F from TC inlet and outlet (no pump) (01:00)
5. Hydroponic flow only (no bubbles) (01:30)
6. Hydroponic flow with Aeration, BD (01:30) *(up to 100% gas diversions observed, up to 100% liquid delivery. Added tests using AIS—bursts and bubble trains)*
7. Hydroponic flow with Aeration, BS, and WT (02:00) *(2 hr of 100% gas-liquid separation observed)*
8. E&F from TC Base test (spot check) (00:30) *(E&F from Base superior)*
9. E&F from TC inlet and outlet test (opt. spot check) (00:30) *(Ingests almost immediately)*
10. Prepare hardware for overnight on MWA (00:20) *(BS safed overnight in dry state using 30 mL Syringe)*

Day 3: (08:30)
1. Ready MWA for PWM tests
2. Remove R4 and Replace with 3 R1 *(Delay locating PWM Plant Root Kit. Satellite drops observed on first 1/3 of inner TC Lid surface)*
3. Repeat Day 2 procedures 2-9 (02:00) *(Somewhat suppressed bubble mergers and escape from TC)*

4. Remove R1 and replace with 3 R2
5. Repeat Day 2 procedures 2-9 (02:00) *(Furukawa reports no bubbles visible in system)*
6. Remove R2 and replace with 3 R3
7. Repeat Day 2 procedures 2-9 (02:00) *(Recover from periodic ingestions with bubble-free TC. Brief excursion to demonstrate dual parallel passive reservoir infill)*
8. BS Limit tests (01:00) *(100% liquid and gas separations before micro-bubbles observed in conduit)*
9. WT Limit tests (with TC bypass) (01:00) *(100% water trap, 100% air exit, < 100% bubble separation in steady two-phase flow mode)*
10. Tear down, Stow (00:30)

During the ≈ 18 hr PWM-5 operations, and depending on how they are counted, ≈ 839 crew setpoint interactions were recorded achieving ≈ 51 E&F tests, ≈ 31 Hydroponics tests (without bubbles), ≈ 18 Hydroponics tests with Aeration, Bubble Diversion, Bubble Separation, and Water Trap, ≈ 76 Bubble Diversion tests, and ≈ 38 Bubbles Separation tests. 'Deeply stable' steady, steady periodic, stable aperiodic, and unstable modes of operation were demonstrated. Hundreds of thousands of oxygenating bubbles were generated and separated. Flow conditions were established under which 100% phase separations were achieved for BS, WT, BD, and TC for various root models. The limits of operation of these capillary fluidic devices are in part established by the PWM-5 tests. The high repeatability of E&F function despite the variability of root zone density and geometry is demonstrated. Dual passive reservoir infill was also demonstrated.

PWM-6 Performance Summary

The PWM-6 demonstrations seek to quantify the impact of TC pinning, contact angle hysteresis, and TC flow resistance due to the presence of the root models on the ability to achieve stable parallel hydroponic flow. The stable long duration performance of capillary devices, BD, BS, and WT are also sought. Increased confidence and TRL are sought with significantly increased operational time for the system. The detailed Crew Procedures are included in Appendix C. Planned procedure details for PWM-6 are listed below with cryptic commentary on outcomes and/or deviations that actually occurred in italic.

PWM-6 ISS Astronaut Crew: Boeing Sunita Williams and Butch Wilmore
Day 0, GMT2024:176, 20 min PWM crew conference
Day 1, GMT2024:177, July 15, 2024: Set-up
Day 2, GMT2024:178, July 16, 2024: Prime and Science Operations
Day 3, GMT2024:179, July 17, 2024: Science Operations

PWM-6 Crew Procedure Details: Planned
Day 0/1: (01:30)
1. Crew Conference
2. Hardware gather/unstow
3. Set-up on MWA

Day 2: (08:30) Root Model R4 in both TCs
1. Reconstitute PWM-provided Fruit Punch drink bags 2 ea 250 mL, and Prime 3 ea 120mL Syringes, and tubing (01:10)
2. Dry TC E&F Base Prime (TCs 1 and 2) (00:10)
3. E&F from TC 1 Base (00:10)
4. E&F from TC 1 inlet and outlet (00:15)
5. E&F from TC 2 Base (00:10)
6. E&F from TC 2 inlet and outlet (00:15)
7. Hydroponic flow TC 1 (00:25)
8. Hydroponic flow with Aeration, BD, TC 1 (00:25) *(Some zoomed footage on BD)*
9. Hydroponic flow with Aeration, BS, WT, BD, TC 1 (01:00)

(Optional) *(Did not pursue)*
Hydroponic flow only TC 2 (00:25)
Hydroponic flow with Aeration, BD, TC 2 (00:25)
Hydroponic flow with Aeration, BS, WT, BD, TC 2 (01:00)

10. Parallel Hydroponic Flow (00:40)

11. Parallel Hydroponic Flow with Aeration, BD, (00:50) *(Appear to establish stable parallel flow limit with Aeration at low pump flowrate F2—hold for 25 min)*
12. Parallel Hydroponic Flow with Aeration, BS, BS, WT, BD (00:50)

(POIC/time permitting) *(Modest time permitted)*

E&F from TC 1 Base test (00:10) *(Tests ingesting gas through TC base, injecting 100% liquid through inlet. Suction applied to BS inadvertently drawing air into BS—easy recovery.)*

E&F from TC 1 inlet/outlet (00:15) *(Not performed)*

E&F from TC 2 Base (00:10) *(Zoom of TC 1 Lid region noting adhered satellite drop size, distribution, and pinning edge status)*

E&F from TC 2 inlet/outlet (00:15) *(Not performed)*

13. Prepare hardware for overnight on MWA (00:20)

Day 3: (08:45) *(Began experiment 1 hr early)*

1. Ready MWA for PWM tests (00:15)
2. Remove R4 and Replace with 3 R1
3. As warranted repeat E&F tests from PWM-6 Day 2 above *(E&F TC 1 only for Base and Outlet, hold-up ~ 28 mL, drain of TC 2 reveals hold-up ~ 45 mL)*
4. Parallel Hydroponic flow (00:30)
5. Parallel Hydroponic flow with Aeration, BD (00:45) *(Small bubbles < 1mm escape BS)*
6. Parallel flow with Aeration, BS, WT, BD (00:45)
7. Remove R1 and replace with R2
8. As warranted repeat E&F tests from PWM-6 Day 2 above *(TC 1 and TC 2 from base only)*
9. Parallel Hydroponic flow (00:30)
10. Parallel Hydroponic flow with Aeration, BD (00:45)
11. Parallel flow with Aeration, BS, WT, BD (00:45)
12. Remove R2 and replace with R3
13. As warranted repeat E&F tests from PWM-6 Day 2 above *(TC 1 and TC 2 from base only)*
14. Parallel Hydroponic flow (00:30)
15. Parallel Hydroponic flow with Aeration, BD (00:45)
16. Parallel flow with Aeration, BS, WT, BD (00:45*) (30 mL Syringe gas injection, zoom to observe BS passing small bubbles, first questioned that BS may be making and passing smalls bubbles. Added spot check E&F test for TC 1 and TC 2 through TC Base. Set Aeration on with Pump set to F2 during ~ 15 min LOS, return of AOS to discover liquid embolism in TC 2 inlet engulfing portion of lid. Discovered PV-11 was not closed completely. Liquid withdrawn using 120 mL Syringe and Tests resumed. E&F tests conducted for two-phase Ebb from TC Base and single-phase liquid Flow through BS and TC inlet)*
17. BS Limits (01:00) *(Only indirectly performed)*
18. WT Limits (with TC bypass) (01:00) *(Not performed)*
19. Tear down and Stow (00:30)

The ≈ 18:45 hr PWM-6 operations completed ≈ 90 E&F tests, 5 bubbly E&F tests, ≈ 50 steady Hydroponics tests with as much as ≈ 30 min maintained without change. Parallel channel flow instabilities are readily observed. Additional limits on device performance were demonstrated for parallel TC flow, serial TC flow, TC gas ingestion, E&F, BS, WT, and BD as functions of root model, TC fill level, and pump flowrate. Specific tests were performed at increased camera zoom, for TC, BS, BD, tubing fittings, and TC pinning edge, lid and stem regions.

PWM-5b Performance Summary

The PWM-5b operations exploited the broadly written PWM-5 Crew Procedures (see PWM-5 procedures, Appendix C) to further investigate flow regime limits of the PWM hardware at higher camera resolution, establish ingestion limits within the TC for all root types R0-R4, and demonstrate the robust response of the system to a broader, less controlled, range of gas-liquid configurations. High resolution performance of the WT was also pursued. Planned procedure details for PWM-5b are listed below with cryptic commentary on outcomes and/or deviations that actually occurred in italic.

PWM-5b ISS Astronaut Crew: NASA Michael Barratt, Matthew Dominick, Jeanette Epps

Day 0, GMT2024:283, October 9, 2024: 20 min PWM crew conference *(not conducted)*

Day 1, GMT2024:284, October 10, 2024: Unstow, Set-up, Prime, and Science Operations

Day 2, GMT2024:285, October 11, 2024: Science Operations

PWM-5b Crew Procedure Details: Planned (10:30)

Again, the crew procedures for PWM-5b are identical to PWM-5. Flexibility within the 'as-written' procedures allowed new PWM demonstrations to be conducted with greater resolution, i.e., TC ingestion limits for all plant root models, BD, BS and WT limits at increased magnification, employment of 'over-the-shoulder' video camera as second science video camera, auto-prime demonstration, and more.

Day 1: (10:30)

1. Hardware gather/unstow
2. Hardware set-up on MWA *(Over-the-shoulder camera set-up in nearly orthogonal orientation. Primary 4K camera zoomed to regions of interest.)*
3. Reconstitute PWM-provided Fruit Punch drink bag, 1ea 250 mL, Prime 120mL Syringes 1 and 2, tubing, Reservoirs, and TC with Root Model R4 in TC (01:00)
4. Dry Test Cell E&F Prime (this is the first test point) (00:10) *(Cavalier auto-prime—without concern for entrapped bubbles, bubble ingestion, etc. Perfect prime achieved via passive bubble separating devices.)*
5. E&F from TC Base tests (no pump) (00:30) *(Some bubbles ingested and injected in rapid E&F.)*
6. E&F from TC inlet and outlet (no pump) (01:00)
7. Hydroponic flow only (no bubbles) (01:30) *(Gas ingestion with both cameras zoomed. Crew handover between Barratt and Dominick)*
8. Hydroponic flow with Aeration, BD (01:30) *(100% gas diversions observed, 100% liquid delivery)*
9. Hydroponic flow with Aeration, BS, and WT (02:00) *(≈ 2 hr of 100% gas-liquid separation observed, upstream Pump tubing de-primed, valve operations required to successfully recover. Pump on to F5, liquid break-through BS first observed. BS continues to function.)*
10. E&F from TC Base test ($Q = 0$) (spot check) (00:30)
11. E&F from TC inlet and outlet test ($Q = 0$) (opt. spot check) (00:30) *(Only performed using TC outlet)*
12. Prepare hardware for overnight on MWA (00:20) *(BS remained wetted overnight, imaged inner Lid of TC.)*

Day 2: (08:20)

1. Ready MWA for PWM tests *(Observe that liquid violating BS has receded to a degree. Begin tests with TC ingestion limit tests with R4)*
2. Remove R4 and Replace with 3 R1 *(TC ingestion limit tests with R1)*
3. Repeat Day 2 procedures 2-9 (02:00) *(E&F through TC Base and Outlet)*
4. Remove R1 and replace with 3 R2 *(TC ingestion limit tests with R2)*
5. Repeat Day 2 procedures 2-9 (02:00) *(E&F through TC Base and Outlet)*
6. Remove R2 and replace with R3 *(TC ingestion limit tests with R3)*
7. Repeat Day 2 procedures 2-9 (02:00) *(BS continues to function, passing only small bubbles despite clearly wetted/fouled by liquid. E&F only through TC Base.)*
8. BS Limit tests (01:00) *(Not performed specifically, but data collected from observations during other tests. Instead, remove R3 and conduct TC ingestion limit tests with no roots, R0.)*
9. WT Limit tests (with TC bypass) (01:00) *(100% water trap, 100% gas exit, < 100% steady two-phase flow separation. Due to Benedikt, under compressed timeline and with uniquely zoomed and illuminated FOV, vary fill level, flowrate, and gas injection rate via 30 mL Syringe to demonstrate single-phase liquid infill, single-phase bubble separations, steady two-phase flow, viscous flow limit, inertial flow transition, cyclonic flow limit, and static drain.)*
10. Tear down, & Stow (00:30)

The ≈ 18:50 hr PWM-5b operations completed include ≈ 48 E&F tests and ≈ 93 shorter duration (~ 5 min) steady single liquid phase Hydroponics tests. Limits on device performance were demonstrated for the capillary fluidic devices of the system with ≈ 68 tests performed for the combined TC, BS, WT, and BD system, ≈ 76 tests specifically for the BD, and ≈ 38 for the BS. A cavalier pump-driven system priming was conducted quickly without regard for trapped bubbles since bubbles are passively 100% separated by plumbing elements of the system. Specific WT tests were completed in haste, but successfully demonstrated water trap, bubble separation, steady two-phase flow, and static drain function. Without consultation from the ground team, crew member Michael Barratt applied the 'over-the-shoulder' camera as an orthogonal zoomed in camera effectively doubling our science footage. This capability led to our immediate change in plan to use one camera for zoomed high–resolution and the other for our original FOV. Again, without consultation, crew member Matthew Dominick configured lighting to resolve fine bubble motion to accurately quantify bubble separation regimes for TC, BD, BS, and WT.

V. Combined Assessment of PWM 5 & 6 Objectives

In total, for PWM-5, -6, and -5b, ≈ 189 E&F tests, ≈ 124 steady Hydroponic flows, and ≈ 306 phase separating limits tests of TC, BS, WT, and BD were conducted. Bracketed by the established limits of operation, the success of the hardware to perform the desired passive functions establishes approximately TRL 7 for the system as well as the various components: TC, Aerator, Reservoirs, Pump, BS, WT, and BD. From a user perspective, mundane plant installation, prime, hydroponic flow $1 \leq Q \leq 5$ mL/s with and without aeration, passive reservoir infill for water and nutrient solution, and easy plant placement and removal are successfully demonstrated by PWM -5, -5b, and -6. In the remainder of this document we report on the PWM data archive, selecting a variety of test results from it that can be applied to advanced system design. Cross-cutting applications of the capillary fluidic demonstrations are suggested in closing.

VI. Data Archive

In total, the PWM-Hydroponics 5, 6, and 5b experiments produced ≈ 55.5 hr of video footage (≈ 100 hr including over-the-shoulder camera). The video data was received from NASA in hundreds of clips which were then carefully spliced into single continuous .mp4 files for each day of operations. Depending on the day, HD or 4K videos were recorded. In the case of GMT:285 PWM-5b, the day's video is split into two spliced videos for Standard HD and 4K portions. The videos were time-stamped to approximate GMT ± 1s.

During the operations, chronological experimental operations are compiled at 1 Hz in Log Files tracking GMT, Crew, Test Operation, Pump Setting, TC (up to 2 ea), Plant Root Model (up to 4 ea), Syringe state (Vol., up to 4 ea), PV state (up to 9 ea), CV state (up to 4 ea), SC state (up to 3 ea), and Res state (up to 2 ea). Many hundreds of thousands of data points were tabulated for each PWM day of operations in this way. The large Log Files are condensed into Summary Tables that include only events for which a significant change to the state of the system was made. The Summary Tables are used to sort PWM operations such as Test Names Prime (PR), E&F tests (EF) and Hydroponics Flow (HF), Hydroponics flows with Aeration (AE), BS, WT, BD, etc. Therefore, one way to sort tests is based on which devices are employed. In order of the flow beginning with the TC these are

PWM#, Test Name, TC, Rx, AE, Res-x, AIS, BS, WT, BD, GMT:ddd:hh:mm:ss,

where Rx is R0-R4 and Res-x is Res-x is Res-1 and -2. Another means of sorting is by flow loop setting i.e., pump, valves, syringes, etc. Any number of methods are possible. [We note that different timestamp conventions were employed over the course of the data reduction. At the time of submission of this report, some such timestamps may have been inappropriately applied to certain events highlighted herein. We apologize for such inconveniences if they arise. The timestamp protocol described above will be adopted exclusively in subsequent reports and publications. The NASA PSI PWM 5 & 6 video archive timestamp convention exclusively adopts the convention above.]

The various events are hyperlinked to the source video corresponding to the GMT of the event. An example screen capture of a portion of the Operations Summary table for PWM-5 is provided in Figure 8. Similar samples are provided in Appendix B for PWM-6 and -5b. The choice of when to demarcate each operation is somewhat subjective. However, actions such as changing the flowrate, changing the flow configuration (i.e., single to parallel flow), changing the type, number, and order of the plant models, etc. are typical examples of actions used. Audio was not always captured in the locally recorded video or may have been recorded but was unintelligible. In such cases, space-to-ground communications were spliced into the downlinked video files and synced to the videos. The Data Log files and Operations Summary spreadsheets are included with all GMT timestamped video records in the PWM 5 & 6 archive.[4] The archive file structure is depicted in Figure 8b.

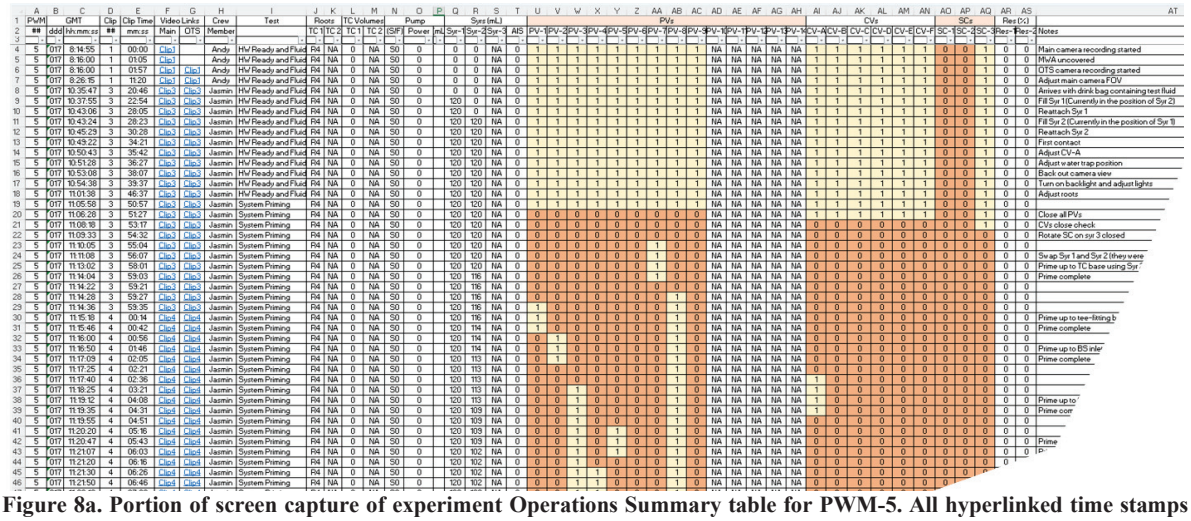


Figure 8a. Portion of screen capture of experiment Operations Summary table for PWM-5. All hyperlinked time stamps correspond to GMT day and time (GMT:ddd:hh:mm:ss) for particular PWM test.

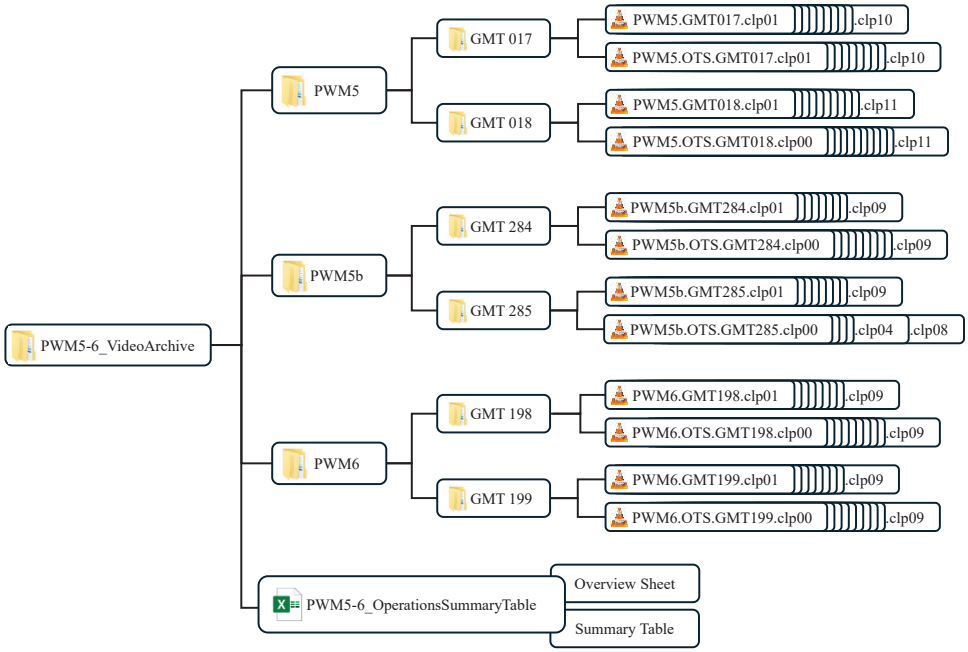


Figure 8b. PWM 5 & 6 archive file structure.

VII. Selection of Data Reduction

The large PWM 5 & 6 dataset is enabled by the breadth of discrete and continuous variables achievable by the PWM hardware. For example, initial conditions can vary widely depending on the nature of the initially primed states of the Fruit Punch Drink Bag, 2 ea 120 mL Syringes, PWM Conduit, Reservoirs, and TC (R0-R4). The E&F tests are functions of root model R0-R4, Syringe and Pump E&F rate, and gas ingestion/injection E&F characteristics. The serial and parallel Hydroponic tests are performed for a continuous variety of liquid fill levels and pump flowrates for the various modes of operation: single-phase liquid flow and two-phase gas-liquid flow with Aeration and BD, Aeration and BS, WT, and BD—with and without air injection (30 mL Syringe). Isolated limit tests are also performed on the Aerator, BS, WT, BD and TC. An exhaustive mining of this dataset cannot be completed under the current contract. As a recourse, we provide a representative sample of data reduction and analysis efforts of value for quantitative assessment of system performance, aid in advanced system design, and insight for space plant watering

trade studies. The list of data reduction and discussion items to be reviewed herein are provided below for root models R0-R4:

A. System Prime: Fruit Punch Drink Bag, 120 mL Syringes, PWM conduit, BD, Reservoirs, TCs, cavalier auto-prime
B. E&F from TC Base, Lower Inlet, and Outlet, with and without gas ingestion/injection, before and after Hydroponics flow tests
C. Hydroponic Flow: steady single-phase liquid Hydroponic Flow and the TC Gas Ingestion limit
D. Hydroponic Flow: Aeration, BD
E. Hydroponic Flow: Aeration, BS, WT, BD
F. Hydroponic Flow: Gas Injection, BS, WT, and BD
G. Hydroponic Flow: Parallel Channel Flow and Limit
H. Passive Reservoirs: Single and Simultaneous
I. Performance Limits and Regimes Maps: Aerator, BS, WT, BD, TC (to appear in subsequent publication)
J. Diagnostics: i.e., In situ Pump calibration, TC volume fill measurement, and others

A. Device and System Prime

Fruit Punch Drink Bags and 120 mL Syringes: The Fruit Punch test fluid is reconstituted for PWM by the crew using the PWD set for 250 mL per bag. Once filled, the bags are needed by hand and allowed to rest for typically > 10 min to fully dissolve the powder drink mix. The entire powder contents of the bag does not always dissolve and rogue bubbles are often introduced into the bag depending on the conditions of the PWD transfer. Additional rogue bubbles are introduced into the liquid when the Fruit Punch is transferred to the 120 mL syringes due to the initially dry state of the syringes. During the first tests, care is taken by the crew to manually centrifuge the syringes and then displace the gas into the cabin. However, as the experiments progressed, because such bubbles are typically small (< 1 mL), because the test channel provides routine bubble separation, and because to disconnect and centrifuge the syringes requires up to several minutes each time, we soon allowed such rogue bubbles to 'play out.' Even during E&F tests when significant gas (< 10 mL) was ingested purposefully or accidentally into the 120 mL Syringes, we simply let them remain only to be reinjected during a subsequent plunge. As a result, quantitative liquid volumes injected and withdrawn by the 120 mL Syringes need to consider gas contents entering or leaving the syringe. This may be accomplished by image analyses and ahistorical accounting of bubble within the syringes which at times is difficult to assess.

For example, unprocessed screen captures before and after a 117 mL – 22 mL = 95 mL plunge of 120 mL Syringe 2 are displayed in Figure 9a and 9c. The low-resolution screen captures are taken for PWM-5 GMT:117 when only RTDL video at 1280x720 px and 30 fps was available. With crude image enhancement, wall-bound bubbles in the syringe are apparent as identified in Figure 9b and 9d. During the plunge, and depending on the plunge rate, small free bubbles are more likely to leave the syringe while wall-bound bubbles tend to merge allowing a more quantitative measure of gas volume in the syringe at low syringe volumes. In this case, estimations of bubble number and volumes from Figure 9d reveal ≈ 2 mL of gas content. Negligible gas left the syringe during this plunge in this instance. Thus, the liquid volume injected is the volume measured via the syringe tick marks. If the entire contents of the syringe were injected, liquid and gas would be injected with the liquid injected being 117 – 2 = 115 mL, or 117 mL ± 2%. Though gathering such information can be a somewhat time-consuming process, despite poor image quality, it is possible in many situations to use syringe history to identify liquid-gas content with reasonable accuracy in the syringes pre- and post-injection and -withdrawal. Related unprocessed images are presented in Figure 9e-h for PWM-5 GMT:118 when 4K download video at 3840x2160 px at 60 fps was available. In such cases, bubble size and number are readily estimated despite poor lighting at times. We thus estimate ≈ 0.5 mL of gas in the 120 mL Syringe 1 both in Figure 9e and 9f. On rare occasion back illumination is employed providing a more accurate assessment of gas hold-up within the syringe as contrasted in Figure 9g and 9h. In most cases, bubble volume in the syringes is small as epitomized in Figure 9e and 9f and liquid volumes injected or withdrawn may be known within the uncertainty of the visual tick mark reading accuracy of ± 1 mL. The PWM demonstrations were not negatively impacted by syringe bubbles since if they ae injected into the loop they are naturally separated by the various devices of the loop: BS, WT, BD, and TC. A degree of accounting via image analysis is required if high syringe bubble volume accuracy is important.

PWM Conduits and Devices: Bubble-free priming of the conduit required ≈ 1 hr with > 50 methodical steps due to the many branching legs of tubing and the slow syringe injection rates required to avoid bubble ingestion and gas slug occlusion (i.e., ref. prime procedure MGUEPWMN020, Appendix C). During the process, priming the PWM 5 & 6 BS, WT, BD, TC, and Res devices was straightforward and successful. The BS was primed with air outlet and liquid

outlet PVs open. The BDs were primed with upper TC inlet PV closed. Once the lower TC inlet was primed, the lower TC inlet PV was closed, the upper TC inlet PV was opened, and the upper TC inlet was primed. The Reservoirs of PWM-5 and -5b were primed to desired levels after opening respective CVs and SCs. The initial fully primed bubble-free states of PWM-5 and -6 are shown in Figure 10 prior to and after the first dry TC prime. The first prime of the TC with R4 installed is referred to as the dry prime. It cannot be repeated. All dry primes are conducted through the TC base port and the TCs are filled to a visually determined height less than the fully pinned fill level. The initial and final states are shown in Figure 10. The TCs fill from the dry root state without event. It is from these primed states that the E&F tests begin.

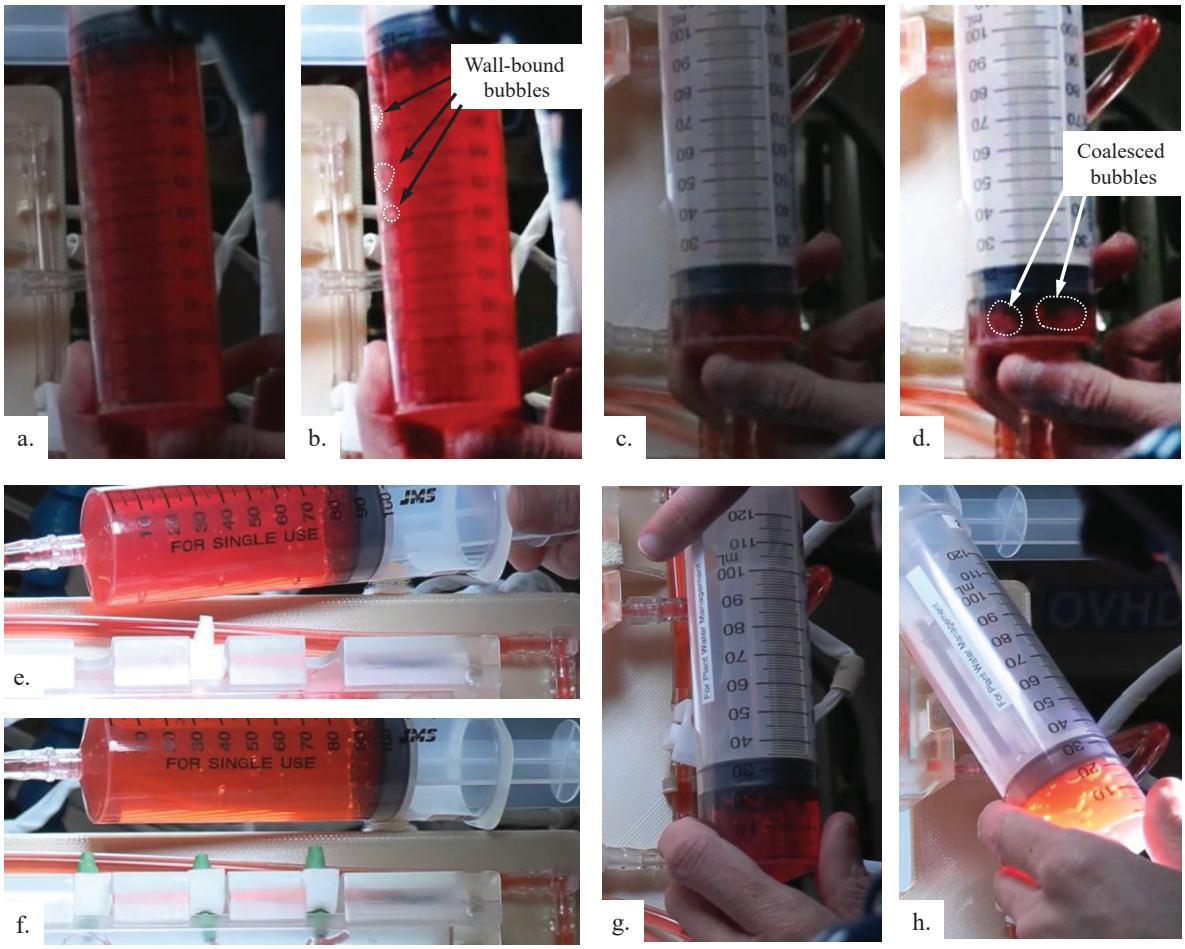


Figure 9. a.-d. Screen captures from PWM-5 of rogue bubbles in 120 mL Syringes at low-resolution RTDL video (1280x720 px at 30 fps, GMT:017) and e.-h. 4K download video (3840x2160 px at 60 fps, GMT:018). Raw images of 120 mL Syringe 2 are shown in a. and c. with crudely enhanced duplicates shown b. and d., respectively, following a 95 mL plunge. The wall bubbles identified in b. are coalesced and somewhat confined as identified in d. where total bubble gas volume in the syringe is < 2 mL. Bubble volume is easier to determine with 4K video for Syringes 1 e. and f. and Syringe 2 g. and h. Backlighting in h. improves quantitative measures. In general, gas volumes are < 2 mL and syringe liquid volume uncertainties from the 120 mL Syringes are ≈ ± 1 mL.

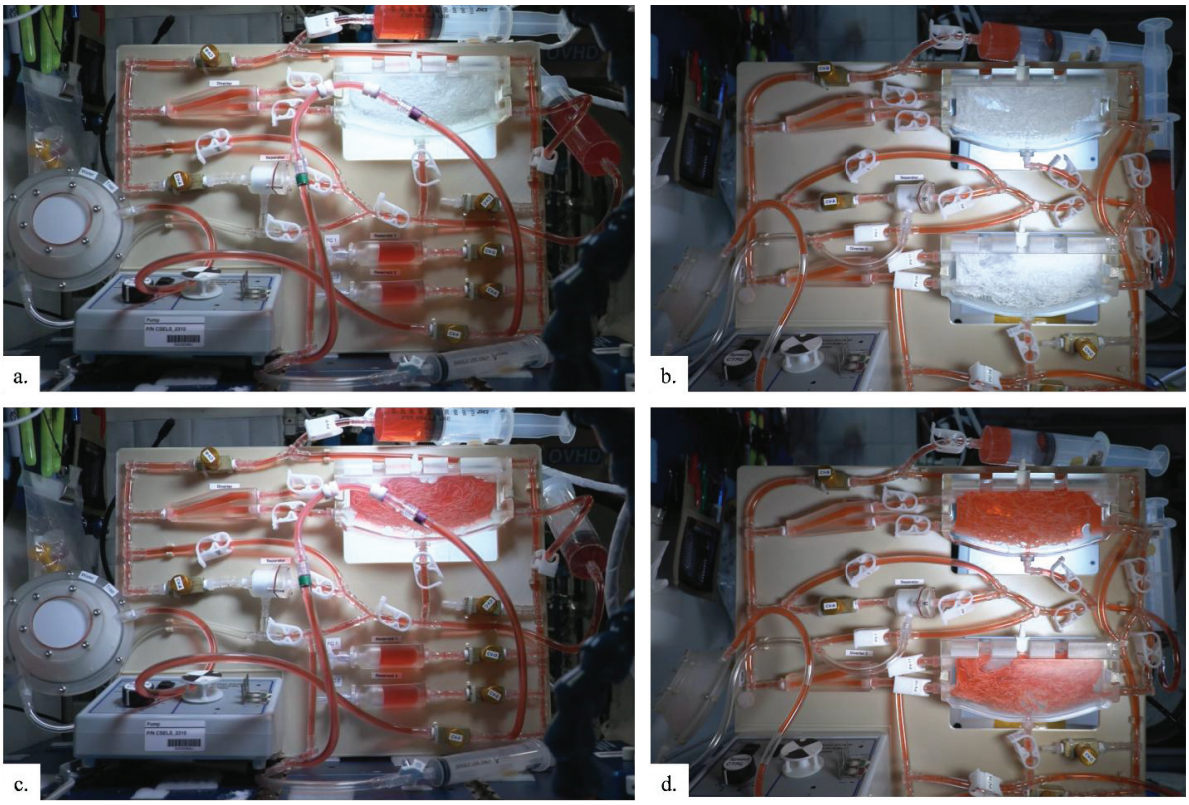


Figure 10. Initial 'bubble-free' primed states for a. PWM-5 (GMT:017-4:39:02) and b. PWM-6 (GMT:198:10:34-01:13:45) with dry TC R4 state prior to E&F tests. Respective primed states following first dry TC fill for c. PWM-5 (GMT:017-4:46:20) and d. PWM-6 (GMT:198:10:34-01:26:22).

Cavalier Auto-Prime: With confidence in the gas separation capabilities of the system, an 'auto-prime' operation was pursued during the PWM-5b tests (GMT:284-15-24:00:28:17). Referring to Figure 1a, for an initially dry system with PV-9, PV-3, PV-4, and PV-5 open (all other valves closed), the plan was simply and elegantly to turn on the pump and prime the most essential legs of the tubing from 120 mL Syringe 1 for hydroponic flow through the TC. We began the process of increasing pump speed until a steady pump head rotation rate could be achieved (F2). Below this rate the pump head would seize producing no flow. Unfortunately, the pump suction pressure at such a low flow rate was not sufficient to overcome the friction of the plunger in 120 mL Syringe 1 and the crew (Barratt) had to manually unseat the plunger by slightly displacing and turning it. During the process, rogue bubbles were entrained into the oscillating advancing flow and the exaggerated gas peristaltic pump action throughout the self-priming portion of the flow. Once the advancing liquid meniscus reached the pump, normal flow was established and continued as desired until we observed that PV-1 was not fully sealed. The pump was shut off, PV-1 was fully closed, and after some consultation it was decided that the final system prime operations would be conducted manually using 120 mL Syringes 1 and 2 per procedure. Ebb & Flow tests were then completed for Root Model R4 in the PWM-5b TC. In the end, the planned 'auto-prime' was neither simple nor elegant. Nonetheless, when the pump was finally turned on to begin Hydroponic tests (~ 1 hr after initiation of the auto-prime test, GMT:284-15-24:01:39:08), all rogue bubbles resident in the system were passively eliminated within one circuit of the loop. Thus, though we did not demonstrate it smoothly, automated bubble-free priming of complex tube harnesses and chambers is mundane provided ample passive bubble separation devices are present—in this case just a BD and TC. In fact, passive recoveries from all purposeful and inadvertent gas ingestion events for PWM 5 & 6 were demonstrated using easily automatable methods.

B. E&F Tests

Most of the E&F states are provided in Figures 11-15 for PWM-5, -5b, and -6, respectively. These images provide clear visual comparisons of the repeatability of the E&F process, which depends mostly on the root model geometry for essentially fixed TC and flowrate ~ 10 to 20 mL/min. We note that there is no significant disturbance to the root

models at these E&F flowrates. E&F flowrates and average flow times are readily determined from the video footage with corrections accounting for gas injected/ingested into/out of the TC, conduit, and 120 mL Syringe. Uncertainties in the volume measurement are nominally ± 1 mL. A more detailed comparison of PWM-5 E&F data from Figure 11 is provided for select back-to-back tests in Figure 12. Typical hold-up volumes are listed in Table 5 for PWM-5 with max Flow volumes $V_{EFmax} = V_{TC} - V_{HU} - V_{RM}$. The repeatability of the E&B states is clear. Initial and final Ebb states are shown in Figure 13 for PWM-5 with R4, between which ≈ 6 hr of Hydroponic Flow testing and overnight dormancy (≈ 12 hr) has transpired. The states remain highly repeatable with similar E&F fill and hold-up volumes as well as visual appearance. From Figure 11 we observe that E&F volumes can be significantly reduced when conducted through TC inlet or outlet ports, the effect of which is amplified with increasing root volume. Poorer Ebb performance is expected from the side ports due to the plant geometry and the longer aspect ratio of the draining process. In certain Ebb cases, gas ingestion is nearly immediate during Ebb leaving nearly the entire liquid contents in the Root bundle within the TC (i.e., R4 inlet, Fig. 11). In general, however, despite poorer performance, E&F behavior through TC lower inlet and outlet remains highly repeatable.

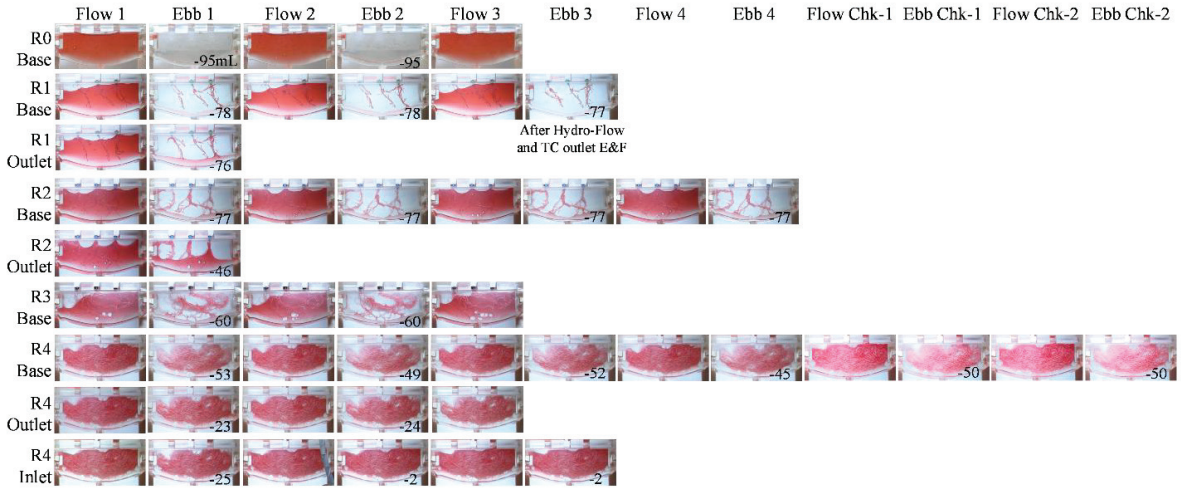


Figure 11. Example of repeat before and after E&F tests for PWM-5 for different Root Models and from different TC ports. Ebb volumes are listed in mL. Spot Check (Chk-#) E&F tests are performed after lengthy Hydroponic flow tests and then overnight showing repeatability of the E&F process for the various Root Models, R0-R4.

E&F tests were conducted where air is ingested either purposefully or inadvertently through the TC base during the Ebb cycle but purposefully separated/eliminated during the Flow cycle by re-routing the Flow through the BS, BD, and TC inlets such that nearly 100% liquid Flows are achieved no matter what occurs during Ebb. In this manner is further control offered by demonstrating high liquid content Flow despite highly two-phase content Ebb. As examples, slugs and bubbles ingested during Ebb and eliminated during Flow are repeatably demonstrated for PWM-5b with R4 (GMT:284-15-24:01:17:00). As discussed in section VII.A above, large gas ingestions reaching the 120 mL Syringes require gas volume balancing to determine accurate liquid E&F volumes, but the majority of the gas ingested during Ebb is removed by the BS, BD, and TC during Flow. Many other examples may be observed (i.e., PWM-6, R4, TC 1, GMT:198-21-13-1298:24:14 and PWM-6 GMT:199-22-03-1307-part2:52:50). A related extreme event is captured during an inadvertent air ingestion during PWM-6 tests when the 120 mL Syringe 3 plunger was retracted while PV-2, PV-4, PV-5, and PV-8 were open. Large gas slugs were ingested through the BS liquid and gas outlet lines and into the syringe (GMT:198-21-13-1298:26:02)—a model for worst case Ebb ingestion. Excellent recovery via elimination of the ingested gas is demonstrated during the subsequent Flow through BS, BD, and TC.

Numerous E&F profiles are provided in Figures 14 and 15. Summarizing the ~ 200 E&F demonstrations for PWM-5, -5b, and -6 we note that for a given root geometry and TC, the E&F process is highly repeatable, particularly when conducted through the most effective TC base port. We find that Ebb volume decreases by up to ≈ 40% between R0 and R4, with > 90% contributions due to liquid hold-up within the root bundle and < 10% due to root bundle displacement (root volume). Some increase in Ebb volume is expected with significantly lower drain rate, but drain port geometry, local drain port region root geometry, and TC aspect ratio significantly limit the degree to which the various root models can be drained.

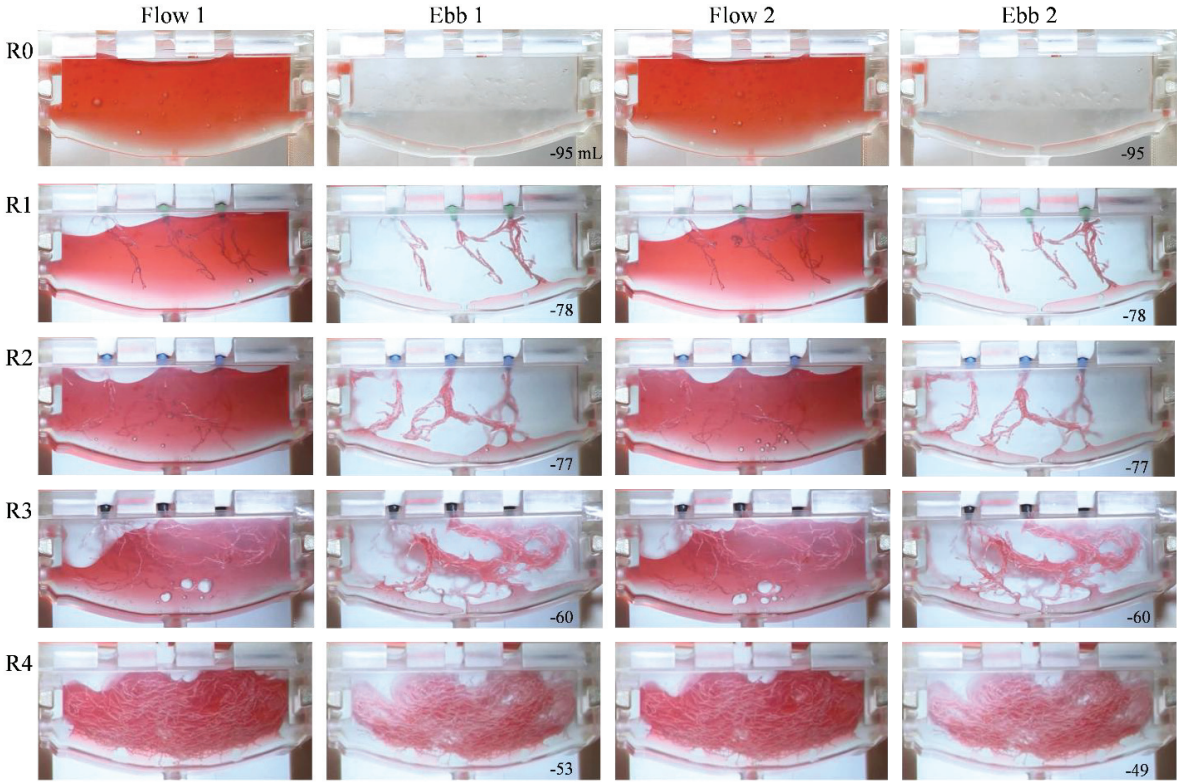


Figure 12. Select back-to-back E&F states for PWM-5 from Figure 11 for R0-R4 draining from TC base and identifying liquid volume removed during Ebb prior to ingestion: ref. Table 5 for Hold-up values.

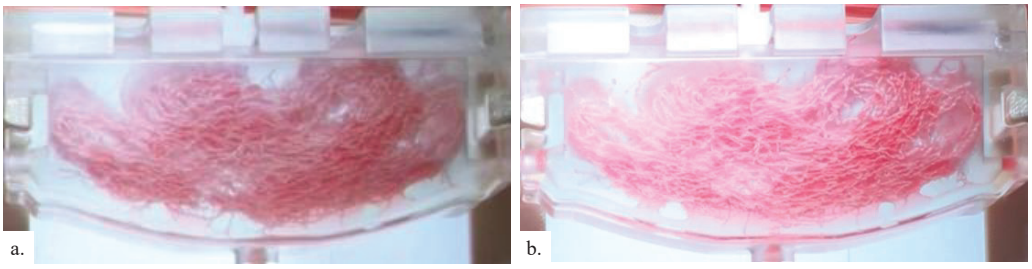


Figure 13. a. First and b. last Ebb states for PWM-5 following ≈ 6 hr of Hydroponic Flow testing and overnight dormancy (≈ 12 hr). The states remain highly repeatable.

Table 5. PWM-5 E&F root model hold-up and root model volume displacements. Note that the hold-up values are for liquid only and that root model displaced volumes for R0, R1, and R2 are negligible. Max Flow volumes are volumes available for liquid.

Root Model	Hold-up (mL)	Root Volume (mL)	Max Flow Volume (mL)
R0	< 1	0.0	112
R1	17	0.1	96
R2	18	0.3	95
R3	34	1.2	78
R4	39	5.2	69

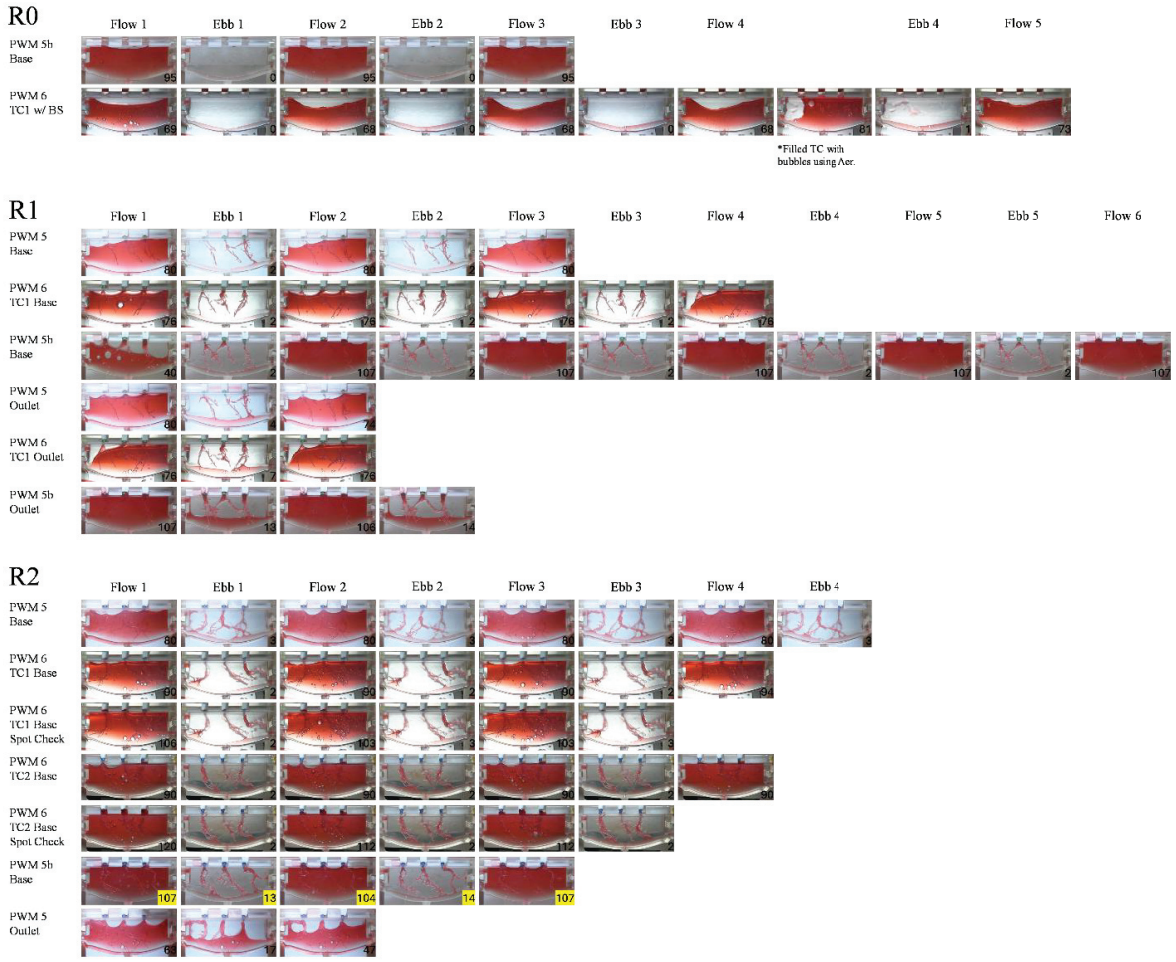


Figure 14. Before and after E&F tests for select PWM-5, -5b, and -6 tests for listed Root Models from different TC ports. Ebb volumes listed in mL.

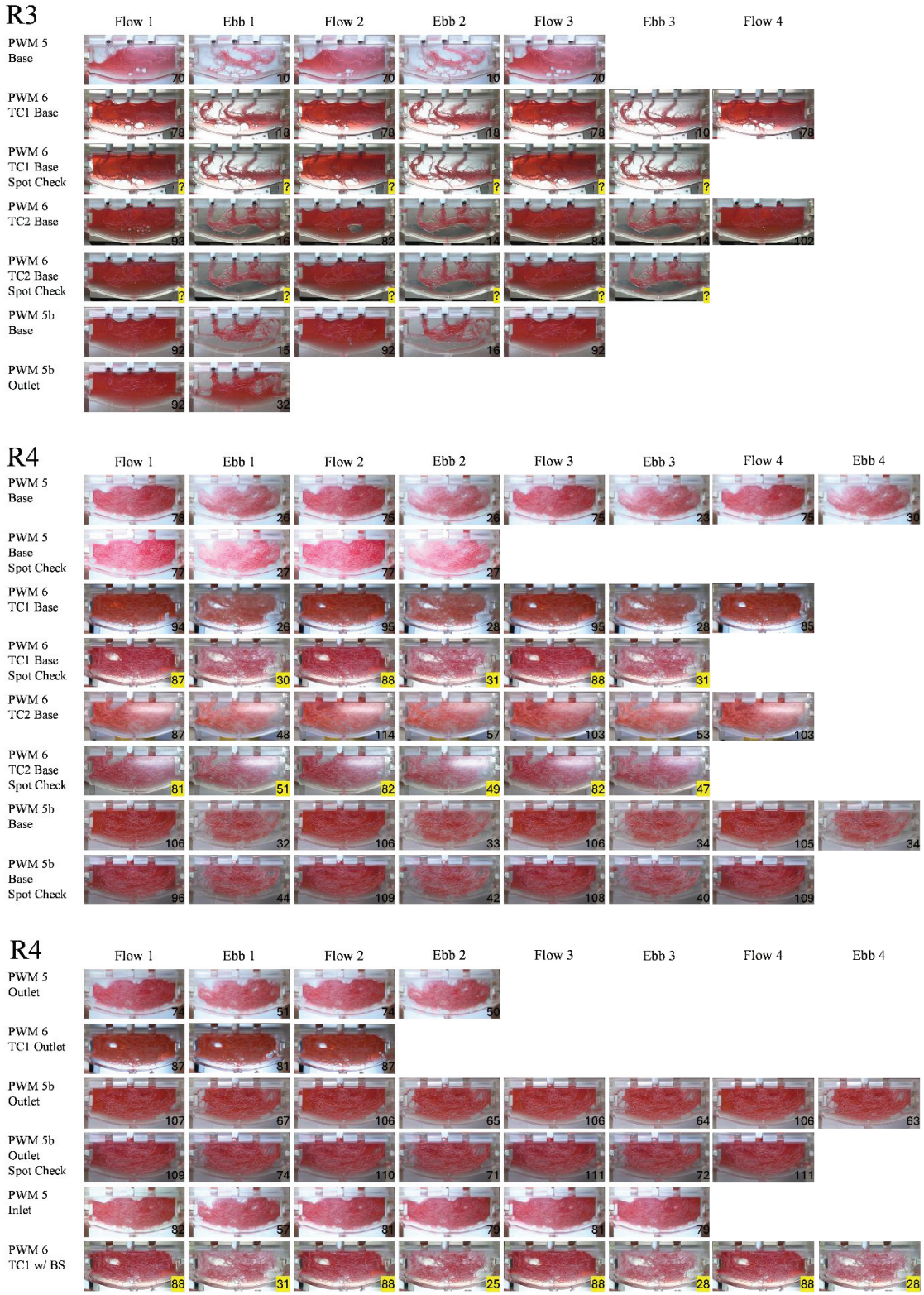


Figure 14 (continued). Before and after E&F tests for select PWM-5, -5b, and -6 tests for listed Root Models from different TC ports. Ebb volumes listed in mL.

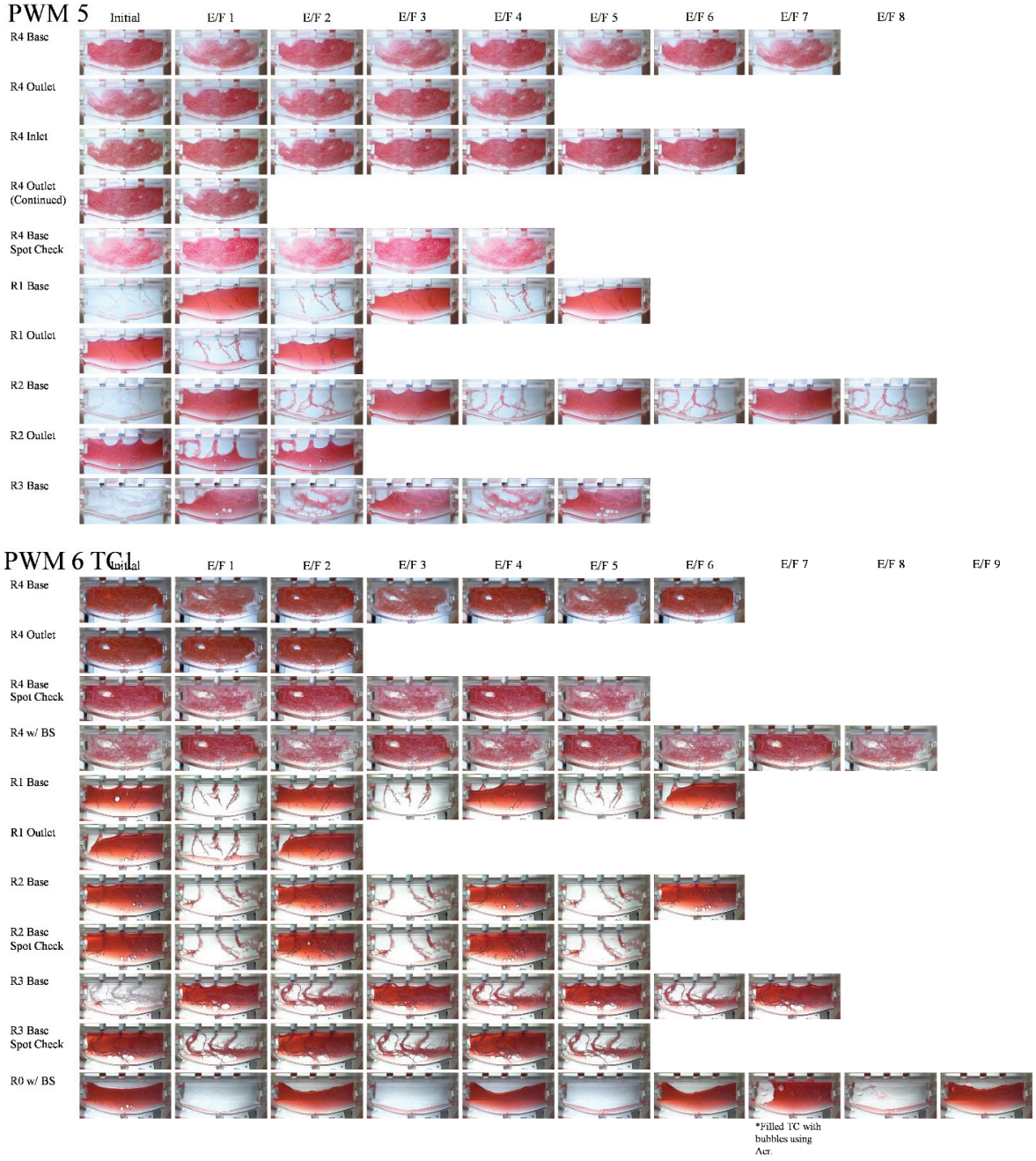


Figure 15. All E&F data in chronological order.

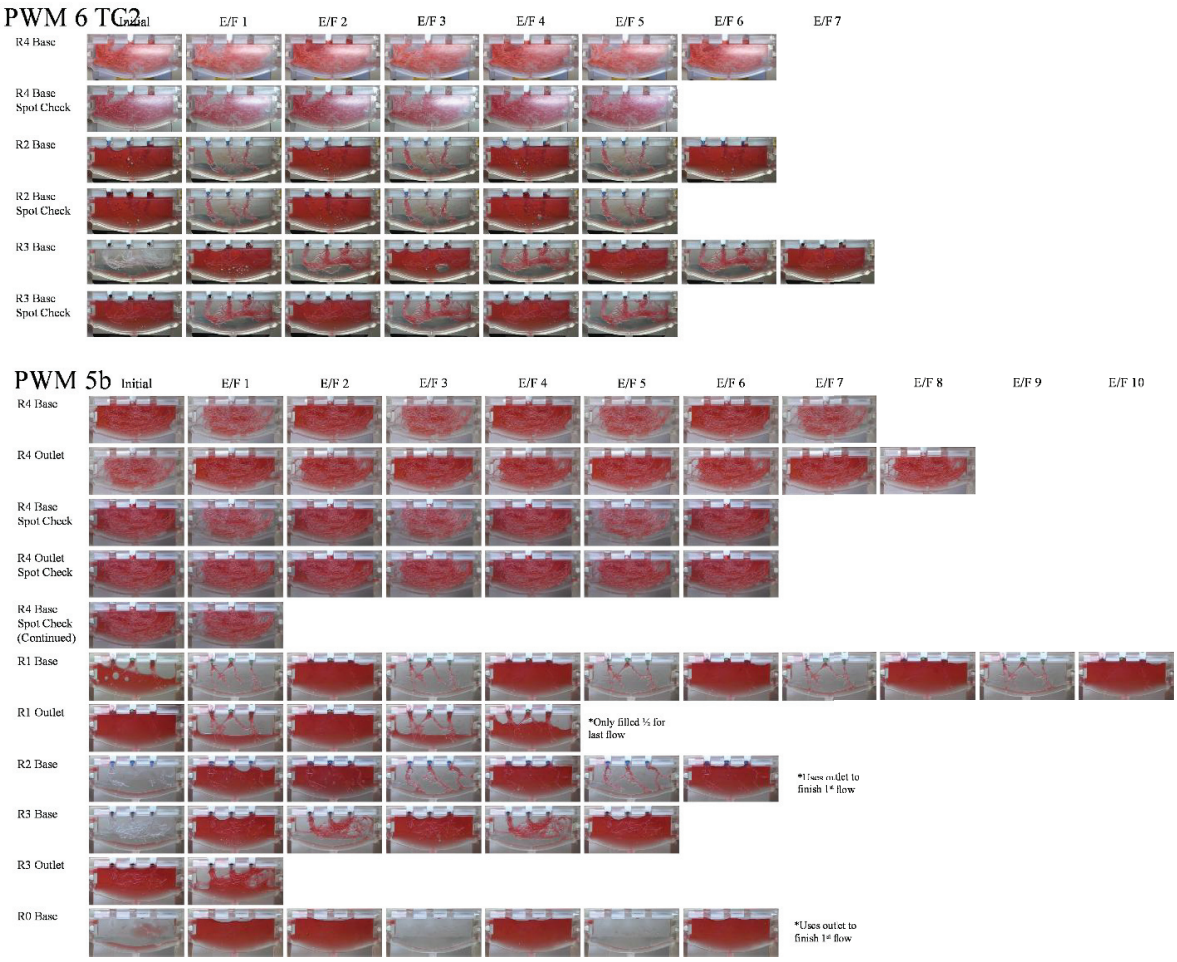


Figure 15 (continued). All E&F data in chronological order.

C. Hydroponic Flow: Steady Single-Phase Liquid Hydroponic Flow and the TC Gas Ingestion limit

The central objective of the PWM Hydroponic technology demonstration is to advance the TRL of hydroponic plant watering methods in microgravity environments. The majority of the PWM 5 & 6 tests were thus conducted to demonstrate the facility of wedge TCs employed for this purpose. Single phase liquid circulation is the first target demonstration with demonstrations to identify the bounds of stable operation in the presence of purposeful and inadvertent bubbly flows to follow.

Single-Phase Liquid Hydroponic Flow Steady States: A selection of steady state single-channel single-phase liquid hydroponic flows is presented in Figure 16. Such images capture the variety of stable fluid interface profiles arising from various pump flow rates $Q_{pump} = Q_l$, TC liquid fill levels V_{TC}, and plant root models R0-R4. The liquid configurations of Figure 16 are stable. The lengthy demonstration in Figure 16 overlays interface profiles at the beginning and the end of the PWM run revealing undiscernible variations within ± 1%, which is below measurement uncertainty of ± 3%.

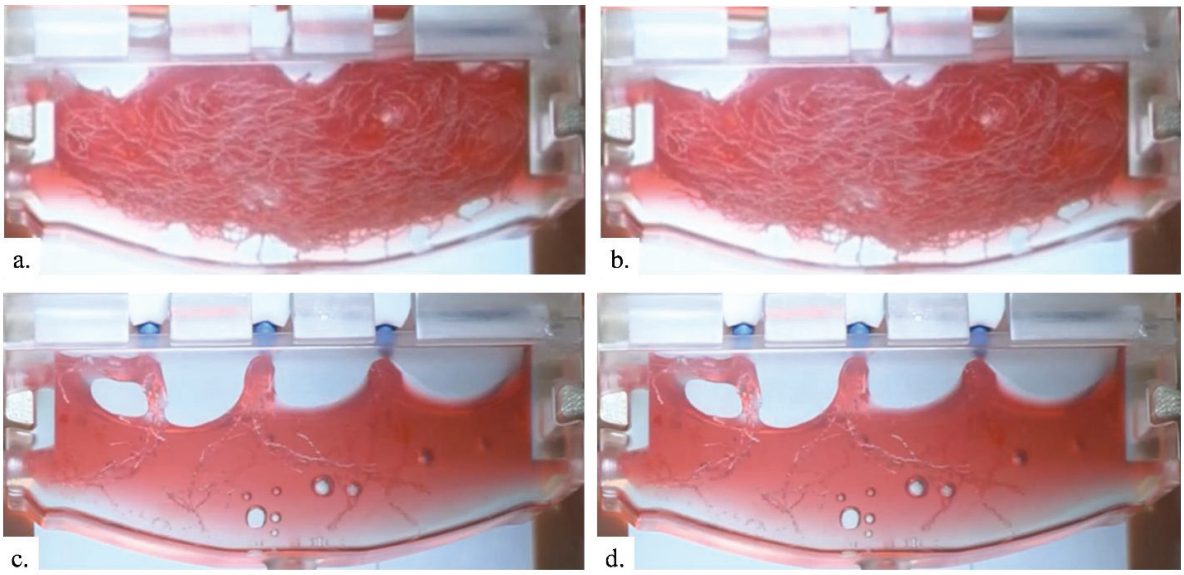


Figure 16. Stable dynamic single liquid phase hydroponic states: a.-b. HD video during ≈ 23 min Hydroponic Flow with R4 at F5 (PWM-5:017:clp04:15:23-38:30) and c.-d. 4K video during ≈ 5 min Hydroponic Flow with R2 at F7 (PWM-5:018:clp06:31:48-36:30). Screen captures b. and d. are indistinguishable form a. and c., respectively.

Stable Hydroponic Flow conditions are established for lengthy times for single and multiple 'plants', varying fill levels, with and without bubbles, etc. Maximum pump flow rates for stable single channel flows were established to be 5.13 mL/s (F10), with approximate minimum flow rates of ≈ 1.77 mL/s (S9). The high rate is limited by the pump speed, while low rate is limited by pump-head tubing tension (i.e., kit-to-kit variations), the lowest speed the pump head could spin without stalling (i.e., PWM-5b Autoprime test). Out-of-plane asymmetries in plant alignment led to local interface deflections observed in the TCs, leading in some cases to local depinning. Such occurrences were not observed to cause instability or degradation in channel performance. Entrance region recirculation zones are readily observed at all flow rates tested and vary in intensity with plant root type, position, and flow rate. These observations are reported in detail elsewhere.[13]

Hydroponic Flow Ingestion Limits. Steady state single-phase liquid hydroponic flow is limited in the TC by gas ingestion at the TC outlet port. The 'ingestion limit' occurs when the liquid flowrate is too high for a given liquid fill level and Root Model/TC resistance. At a critical TC volume ambient gas is ingested at the TC outlet port. At or above the ingestion limit, in general, the gas content ingested through the TC outlet port adds to the fluid volume in the system which acts like additional liquid and soon restabilizes the flow. The now two-phase flow continues to circulate until the gas is (either removed by the BS or) diverted by the BD and removed by the TC. When the gas volume leaves the system, the original lower critical liquid volume is re-established, leading again to gas ingestion at the TC outlet port. This process repeats itself indefinitely as a stable periodic process.

Critically stable states are collected in Figure 17 for PWM-5b just prior to air ingestion at the TC outlet port. TC volumes listed on the figure for TC fill level are those of liquid content only and do not include Root Model displacement volume (ref. Table 4). The added flow resistance of the plant root models reduces the ingestion limit flowrate for a fixed fill level. For these tests pump flowrate is fixed, and liquid volume is iteratively removed via 120 mL Syringe until ingestion is observed. Steady state conditions are held for approximately 2 min or more before liquid is further removed from the TC enroute to the ingestion limit. These steady short duration 'approach' test points are identified as small grey circles in Figure 18. The faint color bands of the ingestion limit flowrates Q_{ling} on the figure identify the empirically unrefined region between the last steady state established and the first stable periodic ingestion state observed. Thus, from the figure we estimate that our measured ingestion limit flowrates are accurate to between ± 2% and ± 8%. Stable (above the curves) and stable periodic regions (below the curves) are identified on the figure. We observe that even the presence of the sparse root model R1 requires obvious increases in channel fill level to maintain ingestion-free flow. We also observe that approximately 3.5-times more liquid is required to avoid ingestion for the packed root model R4 when compared to the no root condition of R0, and that margins on fill volume to avoid ingestion decrease as root zone flow resistance increases. Irregularities in Root Model geometry can yield outlier

events such as the case of R3, where V_{TC} increases with Q as expected, but V_{TC} decreases with increasing Root Model volume (i.e., from R2 to R3). In this instance, the effect is attributed to the complex R3 root geometry and bubble network in the near TC outlet port region which provides a more stable lower capillary pressure liquid configuration allowing for higher flow rate and/or lower V_{TC} at the ingestion limit. In fact, the R3 interface configuration produces an increasing effective depth along the channel as opposed to a decreasing one which is normally the case. Further data on Root Model contributions are listed in Table 5.

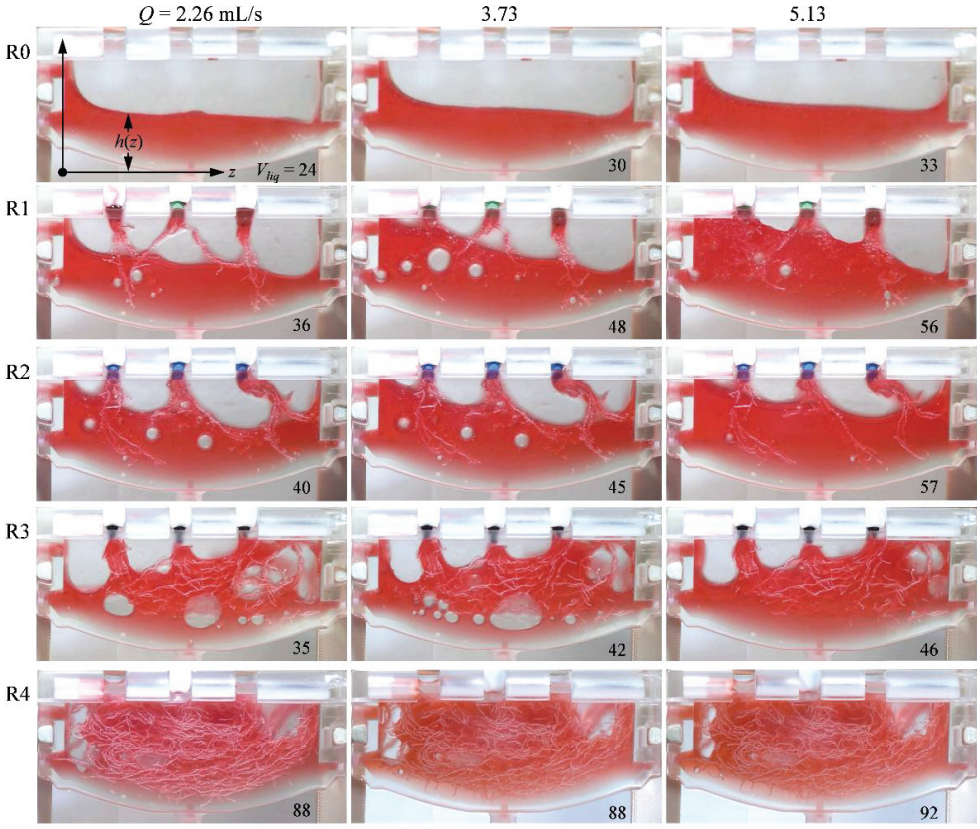


Figure 17. Critically stable images of PWM-5b TC ingestion limit tests for specified single-phase liquid flowrate $Q \approx Q_{ling}$, approximate fill level V_{liq}, and plant root model. For R0-R2, $h(z)$ decreases with z as expected, but for R3 $h(z)$ appears to increase with z, and for R4 any effective change in $h(z)$ is difficult to discern by eye (Volumes in mL). We speculate that the special case of R3 is attributable to the local curvature of confined bubbles at the TC exit.

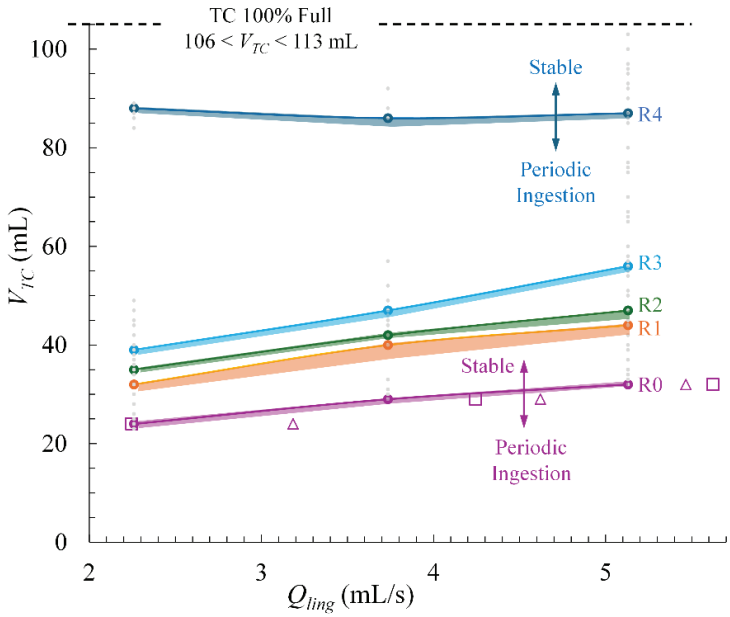


Figure. 18. Plot of single-phase liquid TC gas ingestion limit for PWM-5b plant root models R0-R4. V_{TC} is incrementally removed for fixed Q_{pump} to identify the last stable interface and the onset of steady periodic ingestion, as identified by the banded regions. The small grey test points identify tests completed during the approach to instability. Open purple triangles are approximate predictions based on eqs. (1) - (3) and the assumption of an inertial-visco-capillary along a rootless interior corner flow (i.e., R0). Similarly, open purple squares are approximate predictions based on eqs. (4) – (6) and the assumption of a purely visco-capillary corner flow (R0).

Inertial Hydroponic Flow Ingestion Limit Analysis. Related gas ingestion limits were a central focus of the ISS CCF-EU2 experiment[10]. In that space experiment perfectly wetting HFE-7500 was driven along a $L = 48$ mm long $H = 30$ mm high 'rootless' open wedge channel of half-angle $\alpha = 7.75°$ ($\rho = 1614$ kg/m^3, $\sigma = 0.0162$ N/m, $\mu = 0.00125$ kg/m·s, $\theta = 0°$). The inlet and outlet sections of the channel were enclosed with conduits of identical wedge dimensions. An inertial-visco-capillary scale analysis was pursued to correlate the CCF-EU2 gas ingestion limit data to find

$$Q_{ling} = \frac{\mu L}{2\rho\alpha^2}\left(\left(1+\frac{4}{3}Su^+\right)^{1/2} - 1\right), \tag{1}$$

where

$$Su \equiv \rho\sigma H\alpha/\mu^2 \qquad \text{and} \qquad Su^+ \equiv Su\cdot(H\alpha^2/L)^2. \tag{2}$$

Su is the Suratman number for wedge flow and serves as a measure of inertia in an otherwise visco-capillary flow. The modified Suratman number Su^+ includes more detailed scale dependencies on dimensionless geometry such that $Su^+ << 1$ recovers the visco-capillary limit $Q_{ling} \sim \sigma H^3\alpha^3/3\mu L$, while $(4Su^+/3)^{1/2} >> 1$ recovers the inertial-capillary limit $Q_{ling} \sim (\sigma H^3\alpha/3\rho)^{1/2}$.

Eq. (1) was found valid for $10 < Su^+ < 100$ and accurate to ± 5% for $L/H \geq 1.6$. We note that eq. (1) is contact angle independent. PWM employs a poorly wetting liquid and the PWM TC is not a simple open wedge but possesses an offset cusp vertex that dips in the vicinity of the central base port (ref. Fig. 3). Furthermore, the PWM TCs employ two inlet and one outlet port rather than the uniform entrance and exit ducts of the CCF-EU2 channel. Despite these significant geometric discrepancies, for engineering design purposes we nonetheless pursue an ad hoc method employing eq. (1) to estimate the ingestion rate limited performance of the PWM TC as a function of liquid fill level in the absence of plant roots, R0. We attempt to model the TC as a virtual ideal wedge channel of length $L = 0.15$ m, wedge half-angle $\alpha = 10°$, and virtual wedge height $H_{virt} = 67.5$ mm with uniform wedge inlets and outlets. The relevant properties for the PWM Hydroponics Fruit Punch flows are $\rho = 1000$ kg/m^3, $\sigma = 0.064$ N/m, $\mu = 0.0012$ kg/m·s, and $30° < \theta < 60°$, with wedge cusp height $H_{cusp} = 27.5$ mm identified in Figure 3a. Axial flows are negligible within the H_{cusp} region, thus, the majority of the hydroponic flow is confined within the region between H_{ave} and H_{cusp},

where $H_{ave} = (V_{virtfill}/LF_A)^{1/2} \approx (V_{virtfill}/L\tan\alpha)^{1/2}$ is the approximate average elevation of the liquid level within the virtual TC—as if it was a uniform wedge. The virtual liquid fill level $V_{virtfill} = V_{liq} + \Delta V_{virt}$ is an effective value based the actual liquid volume in the TC V_{liq} plus the solid volume 'occluding' the vertex of the TC and preventing it from being a uniform wedge section with H_{virt}, L, and α. We find $\Delta V_{virt} = V_{virt} - V_{TC} = 120.5 - 113 = 7.5$ mL. Both $V_{virt} = LH_{virt}^2\tan\alpha$ and V_{TC} are confirmed from the TC solid model.

Our ad hoc protocol to estimate Q_{ling} from eq. (1) for the non-ideal wedge flows of the PWM TCs is as follows:

1. For known TC fill level V_{liq}, calculate the virtual fill volume $V_{virtfill} = V_{liq} + \Delta V_{virt} = V_{liq} + 7.5$ mL
2. Compute the virtual average TC fill elevation $H_{ave} = (V_{virtfill}/LF_A)^{1/2} \approx (V_{virtfill}/L\tan\alpha)^{1/2}$
3. Compute $Q_{virtling}$ from eq. (1) using $Su(H_{ave})$ and $Su^+(H_{ave})$
4. Compute Q_{lingTC} by including only the active area portion of wedge flow

$$Q_{lingTC} = Q_{virtling}\left(1 - H_{cusp}^2/H_{ave}^2\right). \tag{3}$$

The experimentally determined ingestion limit data of Figure 18 for R0 are compared with predicted values from eqs. (1)-(3) in Table 6 where qualitative accuracy is observed with over-predictions found of 7, 23, and 42% for V_{liq} = 32, 29, and 24 mL, respectively. These results are added to Figure 19 as open purple triangles and compare adequately to the R0 data for design purposes. For a fully filled virtual wedge TC with $H_{ave} = H \approx 0.064$ m and $V_{virt} = 113$ mL we find $L/H = 2.3 > 1.6$ and $10 < Su^+ = 84 < 100$. Applying eq. (1) we compute $Q_{virtling} = 28.5$ mL/s and from eq. (3) we find $Q_{lingTC} = 23.2$ mL/s. The highest volume fill level with R0 achieved during the PWM tests was 95 mL from which we estimate $Q_{lingTC} = 20.9$ mL/s. These values are far higher than the 5.13 mL/s the PWM pump can deliver.

Table 6. Prediction of inertial ingestion limits in PWM-5b TC using modified eqs. (1)-(3) with fill level and ingestion limit flow rate conditions of R0-R4.

Root Mod.	V_{liq} (mL)	$V_{virtfill}$ (mL)	Pump Setting	Q_{pump} (mL/s)	H_{ave} (m)	Su	Su^+	$Q_{virtling}$ (mL/s)	Q_{lingTC} (mL/s)	Q_{lingTC}/Q_{pump}
R0	113	120.5	-	-	0.0661	513,016	92.5	30.0	24.8	-
	95	102.5	-	-	0.0610	473,150	72.6	26.3	20.9	-
	32	39.5	F10	5.13	0.0379	293,722	17.4	11.6	5.5	1.1
	29	36.5	F5	3.735	0.0364	282,347	15.4	10.8	4.6	1.2
	24	31.5	F2	2.26	0.0338	262,297	12.4	9.4	3.2	1.4
R1	44	51.5	F10	5.13	0.0432	335,383	25.9	14.6	8.7	1.7
	40	47.5	F5	3.73	0.0415	322,095	22.9	13.6	7.7	2.1
	32	39.5	F2	2.26	0.0379	293,722	17.4	11.6	5.5	2.4
R2	47	54.5	F10	5.13	0.0445	345,013	28.1	15.4	9.5	1.9
	42	49.5	F5	3.73	0.0424	328,806	24.4	14.1	8.2	2.2
	35	42.5	F2	2.26	0.0393	304,671	19.4	12.4	6.3	2.8
R3	56	63.5	F10	5.13	0.0480	372,412	35.4	17.6	11.8	2.3
	47	54.5	F5	3.73	0.0445	345,013	28.1	15.4	9.5	2.5
	39	46.5	F2	2.26	0.0411	318,687	22.2	13.4	7.4	3.3
R4	87	94.5	F10	5.13	0.0586	454,311	64.3	24.6	19.1	3.7
	86	93.5	F5	3.73	0.0583	451,901	63.3	24.3	18.9	5.1
	88	95.5	F2	2.26	0.0589	456,708	65.3	24.8	19.4	8.6

Similar ingestion limit predictions are made for the R1-R4 data of Figure 17 as listed in Table 7. Comparing ratios of Q_{lingTC}/Q_{pump} we observe the impacts of Root Model geometry on reduced ingestion limit flow rates where over-predictions in Q_{ling} are as high as 240% for the case of R1 $V_{liq} = 32$ mL. The mere presence of the slightest plant root is observed to reduce the critical ingestion limit flow rate by over half. Extreme reductions in ingestion limit flow rate is expected of up to ≈ 860% for R4 at high fill levels. Greater reductions are expected with increased root density. Flowrates in excess of the steady periodic ingestion limit tests discussed in this section lead to the truly unstable situation of 100% or nearly 100% gas ingestion at the TC outlet port and potentially unrecoverable liquid overflow at the TC inlet. Though this level of gas ingestion was demonstrated during the PWM 5 & 6 tests, at the risk of releasing liquid into the ISS cabin, such tests were not permitted to 'run-on' to observe whether the periodic ingestion state would indeed recover. It seems unlikely.

Viscous Hydroponic Flow Ingestion Limit Analysis. The well-established analytic solution[3] for the steady capillary flow of a viscous liquid along a virtual wedge channel may be similarly modified to predict the ingestion limit in the PWM TCs for R0. In the zero-gravity limit of parallel virtual wedge flow, the steady volumetric visco-capillary flow rate along the channel may be written

$$Q_{\mu virtling} = \frac{\sigma}{\mu}\frac{H_1^3 F_A}{3L}\frac{F_i \sin^2\alpha}{f}\left(1 - \frac{H_2^3}{H_1^3}\right), \tag{4}$$

where

$$F_A = f^2\left(\frac{\cos\theta \sin\delta}{\sin\alpha} - \delta\right) \qquad \text{and} \qquad f = \frac{\sin\alpha}{\cos\theta - \sin\alpha}, \tag{5}$$

and where $F_i \approx 1/7$ is a numerical flow resistant coefficient. H_1 and H_2 are the upstream (inlet) and downstream (outlet) meniscus heights respectively, neither of which are easily identified for the TC flows and both of which are complicated by local 3-d capillary curvature due to wedge end effects. F_A and f are dimensionless section area and interface curvature functions and $\delta \equiv \pi/2 - \alpha - \theta$ as described in Ref. 3. Eq. (4) is valid primarily if the flow is predominately parallel, which is assured when $Su^+F_i/\alpha << 1$, where $\tan\alpha \approx \alpha$ is applied. Flow rates above $Q_{\mu virtling}$ result in gas ingestion.

For gas ingestion in an ideal wedge channel $H_2 \approx 0$, but for the TC one might choose $H_2 \approx H_{cusp} = 0.0275$ m. Furthermore, the wedge flow in the region below H_{cusp} is largely occluded by the cusp region detail. Subtracting the flow in this virtual wedge vertex region and again choosing $H_1 \approx H_{ave} = (V_{virtfill}/LF_A)^{1/2}$ in an ad hac manner we modify eq. (4) to

$$Q_{\mu lingTC} = Q_{\mu virtling}\left(1 - \frac{H_{cusp}^3}{H_{ave}^3}\right) = \frac{\sigma}{\mu}\frac{H_{ave}^3 F_A}{3L}\frac{F_i \sin^2\alpha}{f}\left(1 - \frac{H_{cusp}^3}{H_{ave}^3}\right)^2. \tag{6}$$

All conditions of Table 5 for the PWM-5b ingestion limits are re-compared to values calculated using eq. (6) in Table 7, despite the fact that only for R0 does the eq. (6) even approximately apply. In these cases over-predictions of ≤ 10% are found for the lowest though still elevated Su^+F_i/α values ~ $O(10)$, indicating the order of magnitude of inertia present in the TC flow for R0 at the lowest fill levels. The agreement increases as inertia decreases as might be expected. The eq. (6) results for R0 are added to Figure 18. These values adequately agree with both the data and inertial predictions of eqs. (1) – (3) and thus both inertial and viscous approaches appear to overlap for this flow regime and may be useful for engineering design purposes. For the viscous model, extreme reductions in ingestion limit flow rate is expected of up to ≈ 1980% for R4 at high fill levels. Clearly both inertial and viscous models are incapable of predicting ingestion limit behavior with Root Models unless the geometric complexities the roots pose to local capillary pressure and viscous resistance area accounted.

D. Hydroponic Flow: 'Steady' Periodic Ingestion

As introduced above, the PWM Hydroponic ingestion limit gives rise to a stable periodic mode of operation of the loop—one which is not immediately in danger of dry-out or over-filling. The ingested gas momentarily restabilizes the free surface only to ingest again once the gas ingested is separated and leaves the flow at the TC (or BS) by the combined effects of the BD and TC (or BS, BD, and TC). As an example, 8 periodic ingestions occur during return to steady stable flow after an excursion in flowrate from F8 to F8.5 then back to F8 resulting in the onset and recovery from periodic ingestions during PWM-5 operations (PWM5:GMT017:clp07:18:04-19:12). The fill level of the TC is $V_{TC} = 63$ mL and Q_{pump}(F8) = 2.98 mL/s with R4. The average measured volume of gas periodically ingested is 0.56 ± 0.05 mL. Thus, in this case the instability is recovered by an approximately 0.56 mL gas ingestion in response to the F8 to F8.5 increase in Q_{pump}. Near the periodic ingestion limit the measured average period of ingestion is t_{per} = 7.2 s ± 3 s, which corresponds well with tubing harness circulation time estimation of

$$t_{tub} \approx \frac{V_{tub}}{Q_{pump}} = \frac{35xx\ \text{mL}}{2.98\frac{\text{mL}}{\text{s}}} = 7.5\ \text{s}. \tag{7}$$

In another example, the ingestion limit is established for flows with and without AE. In one case (PWM5.GMT017.main.clp7.48:00-49:29) for PWM-5 with F5 (Q_{pump} = 2.2 mL/s, $Q_l = Q_{pump} - Q_g \approx 1.9$ mL/s), R4, V_{TC} = 54.5 mL, and AE set to CV-C to N4, 5 steady periodic ingestions are established with essentially 3.8 ± 0.3 mL gas slugs, from which t_{per} = 16.8 ± 0.4 s. The base flow is aerated with a total gas content in the tubing harness based on this 12% aeration level estimated by counting bubbles of measured diameter to be 4.3 mL gas in the upstream and downstream tubing. The total gas content during the period of ingest is therefore approximately 3.8 + 4.3 ≈ 8.1 mL. The aeration valve CV-C is then closed (PWM5.GMT017.main.clp7.49:43-52:29) and within 68 s the loop achieves a new aeration-free periodic ingestion state observed for 10 ingestions with nearly unchanged t_{per} = 16.6 ± 0.5 s, for a nearly unchanged gas ingestion volume of 8.5 ± 0.1 mL. The liquid flowrate Q_l is increased by as much as 12% from 1.9 to 2.2 mL/s when CV-C is closed. This change in Q_l is not significant enough to mask the steady periodic nature of the periodic ingestion limit which establishes nearly identical periodicity and ingested gas volume whether in single phase liquid flow or aeration flow with Q_{pump} fixed. Computing the tubing harness circulation time from eq. (7) for this flow we find $t_{tub} \approx 35/2.2 = 15.9$ s, which is within 4% of the measured values. Thus, PWM 5 & 6 periodic ingestion is well behaved: periodically stable, of known periodicity, and of fixed gas volume ingestion which increases with decreasing Q_{pump}. It also provides a natural stable passive aeration function. In use with the BS, ingested bubbles never enter the TC.

Table 7. Prediction of viscous ingestion limits in PWM-5b TC using modified eqs. (4)-(6) with fill level and ingestion limit flow rate conditions of R0-R4. (Compare with Table 5 values for R0.)

Root Mod.	V_{liq} (mL)	$V_{virtfill}$ (mL)	Q_{pump} (mL/s)	H_{ave} (m)	H_2 (m)	Su	Su^+F_i/α	$Q_{\mu virtling}$ (mL/s)	$Q_{\mu lingTC}$ (mL/s)	$Q_{\mu lingTC}/Q_{pump}$
R0	113	120.5	-	0.0661	0	513,016	73.0	78.7	78.7	-
	95	102.5	-	0.0610	0.0275	473,150	57.3	73.1	67.8	-
	32	39.5	5.13	0.0379	0.0275	293,722	13.7	9.1	5.6	1.1
	29	36.5	3.735	0.0364	0.0275	282,347	12.2	7.5	4.2	1.1
	24	31.5	2.26	0.0338	0.0275	262,297	9.8	4.9	2.2	1.0
R1	44	51.5	5.13	0.0432	0.0275	335,383	20.4	16.3	12.1	2.4
	40	47.5	3.73	0.0415	0.0275	322,095	18.1	13.8	9.8	2.6
	32	39.5	2.26	0.0379	0.0275	293,722	13.7	9.1	5.6	2.5
R2	47	54.5	5.13	0.0445	0.0275	345,013	22.2	18.3	14.0	2.7
	42	49.5	3.73	0.0424	0.0275	328,806	19.2	15.1	11.0	2.9
	35	42.5	2.26	0.0393	0.0275	304,671	15.3	10.8	7.1	3.1
R3	56	63.5	5.13	0.0480	0.0275	372,412	27.9	24.5	19.9	3.9
	47	54.5	3.73	0.0445	0.0275	345,013	22.2	18.3	14.0	3.7
	39	46.5	2.26	0.0411	0.0275	318,687	17.5	13.2	9.2	4.1
R4	87	94.5	5.13	0.0586	0.0275	454,311	50.7	49.0	43.9	8.6
	86	93.5	3.73	0.0583	0.0275	451,901	49.9	48.1	43.1	11.5
	88	95.5	2.26	0.0589	0.0275	456,708	51.5	49.9	44.8	19.8

E. Hydroponic Flow: Aeration, BD

Any plant watering system for application in space must account for the presence of bubbles whether produced *inadvertently* by trapped gas, degassing, or biochemistry, or *purposely* by bubble ingestion or direct injection for liquid aeration. Because inadvertent bubbles have the potential to completely destabilize such capillary flows, and because plants in low-g environments often suffer from hypoxic conditions, PWM 5 & 6 dedicated over ~ 7 hours of experiment time to investigating bubbly flows in the loops. At least 129 PWM-5, -5b, and -6 tests were conducted towards this end. In general, we find that the PWM hardware is largely insensitive to the presence of bubbles due to the redundant passive bubble separating devices (BS, BD, and TC/Root Model). A host of destinations for such bubbles are observed. With all devices plumbed, ≈ 100% bubbles are separated by the BS. Those that 'pass' are diverted by the BD into the upper entrance region of the TC. These bubbles may become temporarily trapped in recirculation zones within the TC created in part by the presence of the plant roots. They may be trapped by such roots, become wall-bound, grow by mergers until confined, and then rise in the channel capillary forces only to coalesce with the free surface and leave the flow. Bubbles < 1 mm circulate through the loop, but even these appear to eventually become trapped, wall-bound, dissolve, or coalesce into larger bubbles which are then separated by the next device downstream. We note that no bubbles are observed to escape the TC when packed roots are present (i.e., R4).

The BD was designed with the intention to improve the gas separation efficiency of the TC by introducing the bubbles close to the TC free surface. The BD exploits its own bubble point allowing only liquid to pass into the lower TC inlet, while excluding bubbles and directing them into the upper TC inlet. To demonstrate the performance of the BD, the Aerator is employed producing variable trains of bubbles upstream of the pump, or the AIS is employed injecting variable bubble trains downstream of the pump. TC fill level, pump flowrate, flowrate ratio, and Root Models are varied during such tests representing all independent parameters for the BD demonstrations and such that BD separation efficiency may be quantitatively established in a regime. We provide only a terse display of such data herein.

Example still images are presented in Figure 19 for Hydroponic flow with Aeration and BD operation. The figure selects cases from PWM-5b with R4 in the TC for increasing Aeration rates and fixed pump flowrate. In Figures 20b-d, zoomed 4K video reveals 100% sub-liminal diversion, 100% liminal diversion, and > 95% super-liminal diversion, respectively. These conditions are created by increasing the degree of aeration for fixed pump flowrate. 100% BD diversions assure 100% liquid delivered to the TC base assuring and thus ≈ 100% gas separation in and by the TC/Root Model system. The diverter limit in this instance is observed when bubble densities increase to the point of a coarsening 'foam' of increased viscous resistance. The increasing ΔP eventually exceeds the bubble point of the BD screen leading to aperiodic gas breakthrough at the critical point. The gas content at breakthrough increases with increasing gas content and pump flowrate. Below such flow limits identified during PWM testing, the BD combined with the TC and Root Model serve the role of 100% separation of a wide variety of rogue or purposely aerating bubbles. The PWM BD is currently assessed at TRL 7.

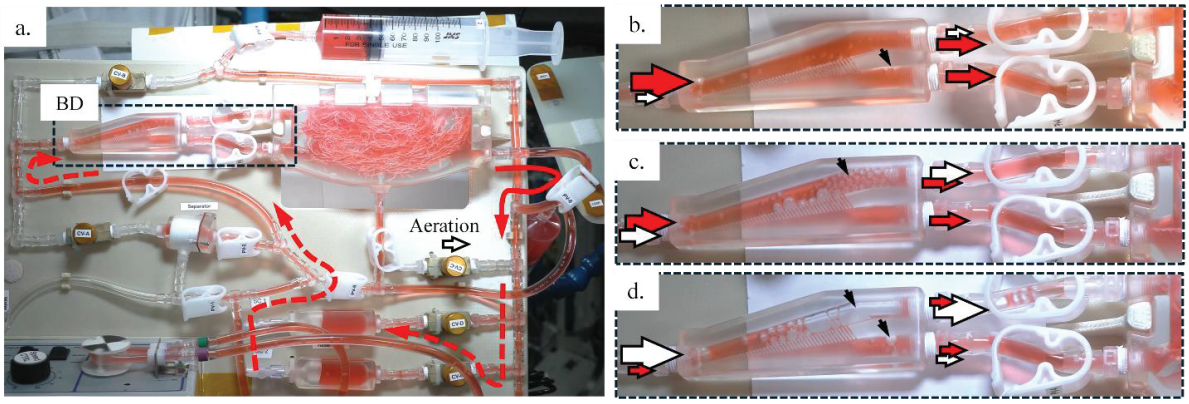


Figure 19. a. Image of PWM-5b Hydroponic flow with Aeration and Bubble Diversion (black dashed region) with solid red arrows indicating single phase liquid flow, white arrow Aeration flow, and dashed red arrows 2-phase flow. Close up images of BD during tests of increasing gas flow ratio: b. 100% gas diversion mode, e. liminal 100% gas diversion mode, and d. super-liminal mode where gas flow rate exceeds BD bubble point leading to gas breakthrough with flowrates notionally indicated by arrow size. The small black arrow in b. identifies small stationary wall-bound bubbles, c. bubble/foam confinement and back-up, and d. bubble coarsening and breakthrough.

F. Hydroponic Flow: Aeration, BS, WT, BD

In a similar manner to the Hydroponics tests with Aeration and BD, numerous Hydroponic flow demonstrations of passive bubble separation were conducted for Aeration, BS (with WT), BD and TC with Root Model. Flowrate variation along with Aeration or gas injection through the AIS are used to map BS conditions of 100% separation. A brief presentation is provided in Figure 20 where the general plumbing circuit is shown with select magnified images of BS performance illustrating the approach to the bubble point limits of operation from the 100% phase separation regime. These limits are found in part by turning down CV-A increasing the pressure within the BS to the point of liquid breakthrough. Tests performed beyond the breakthrough limit are performed to demonstrate 100% liquid trap and separation in the WT to be discussed shortly. Two-phase flow regimes (i.e., flowrates and flow rate ratios) are also varied to identify bubble carry-over limits of the BS device, where ≤ 1 mm diameter bubbles are first observed to escape the BS liquid outlet line. Hundreds of BS tests were performed, many of which are used to construct BS performance regime maps as shown in Figure 21 for CV-A wide open, where the pink region identifies the empirically determined region of 100% phase separation, while other regions represent regimes of partial separation < 100%. Such maps are produced for fixed flow resistance values as set by CV-A. The liquid breakthrough limit is not observed in the Figure 21b map since CV-A is wide open and pump flowrates are limited. Such limits were observed and will be

included in subsequent maps as the data in the archive is further reduced. An overall degradation in BS performance is observed

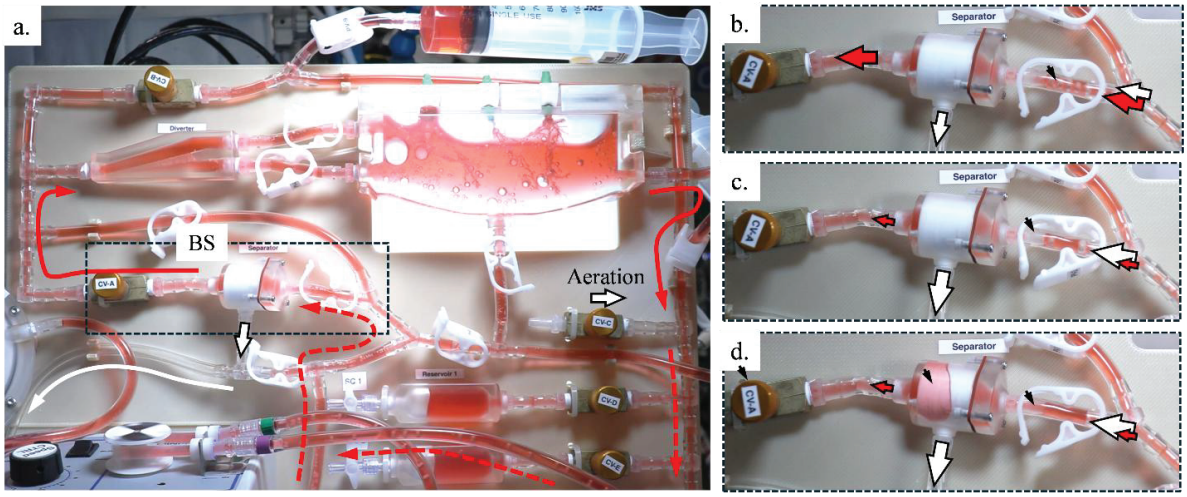


Figure 20. a. PWM-5 Hydroponic flow tests with Aeration, BS, BD, and TC with R1—100% gas separation is achieved by the BS with 100% gas (white arrow) vented to atmosphere and 100% liquid (solid red arrow) returning to loop. Dashed red arrows denote two-phase flow. Zoomed 4K video of BS performance varying flow rate, gas content, and system pressure: b. 100% separation for low gas content bubble flow (black arrow), c. 100% separation for high gas content gas slug flow (black arrow), and d. bubble point liquid breakthrough limit (black arrow) for a gas slug flow (black arrow) achieved by increasing downstream pressure via turning down CV-A (black arrow).

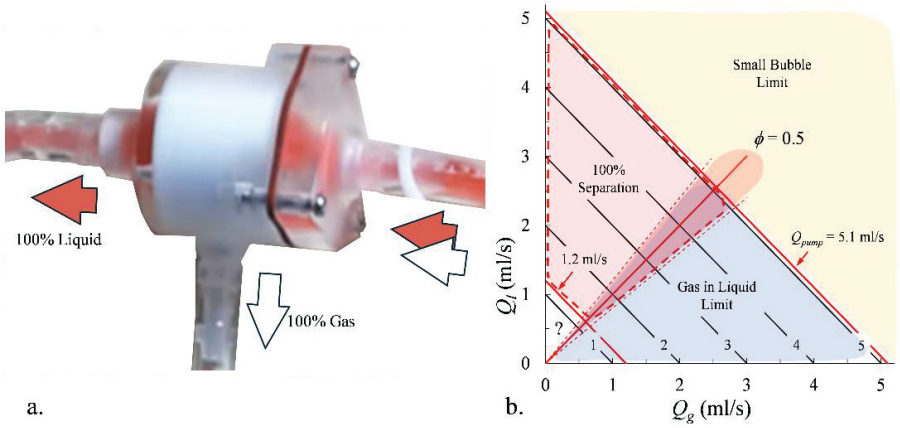


Figure 21. a. Cut away image of BS during 100% separation operation (pink region) with liquid (red) and gas (white). b. Preliminary regime map of BS performance for data collected with CV-A wide open. The overlap region signifies irregular separation. The question mark region is expected to yield 100% separation as well but could not be tested due to the low flowrate limit of the pump.

G. Hydroponic Flow: Gas Injection via AIS, BS, WT, and BD

Gas injection via the AIS has the advantage of providing additional control over the BS inlet bubble flow regime since the bubbles are injected downstream of the peristaltic pump and do not get churned by it. The flows are still somewhat disrupted by the fittings (i.e., Tee fittings) at elevated flow rates, but remain regular and ordered at low flowrates despite 'steady manual' gas injection rates of the crew. Such tests provide highly quantitative data for BS efficiency assessments and will be pursued and published separately. Purposeful and inadvertent gas injection using the 120 mL Syringes was also observed achieving very low flowrates demonstrating 100% BS separation for all flowrate ratios—100% separation for 100% gas flow, 100% separation for 100% liquid flow, and 100% separation for everything in between. This is an attractive low flowrate regime for the BS device. It is identified by the '?' in Figure 21.

H. Hydroponic Flow: Parallel Channel Flow

Stable parallel open capillary Wedge channel flows have been thoroughly demonstrated during previous space experiments with 2, 4, and 16 parallel channels.[13] With sufficient fill level, pinning, contact angle hysteresis, and limits on bubbly flow and flow rates, stable flows are achievable. Prior work has also demonstrated that manifold flow resistance is often greater than that of open channels[14] and can play a significant role in flow balancing. PWM-Hydroponics 3 & 4 added the complications of larger test cells, plants as obstacles, elevated flow rates, and a plethora of bubbles and bubble distributions in both channels and manifolds.[3] PWM 5 & 6 provides further data on un/balanced flows in the presence of more realistic Models. In Figure 22a, the TCs with R4 are filled with approximately the same volume of liquid, the system plumbed for parallel flow, and the pump turned on. A slow transfer of liquid is observed from TC2 to TC1 over a 5 min period (see black arrow in Fig. 22b). This transfer appears to be all that is necessary to balance hydrodynamic and capillary pressures since the liquid profiles in the TCs no longer change for a 'deep steady state' of 25 min. Incremental increases in flowrate result in further shifts eventually to the point of gas ingestion at the TC2 outlet, or liquid overflow at the TC1 inlet. Both were observed. In this way the limits of stable parallel flow are determined to be published at a late date.

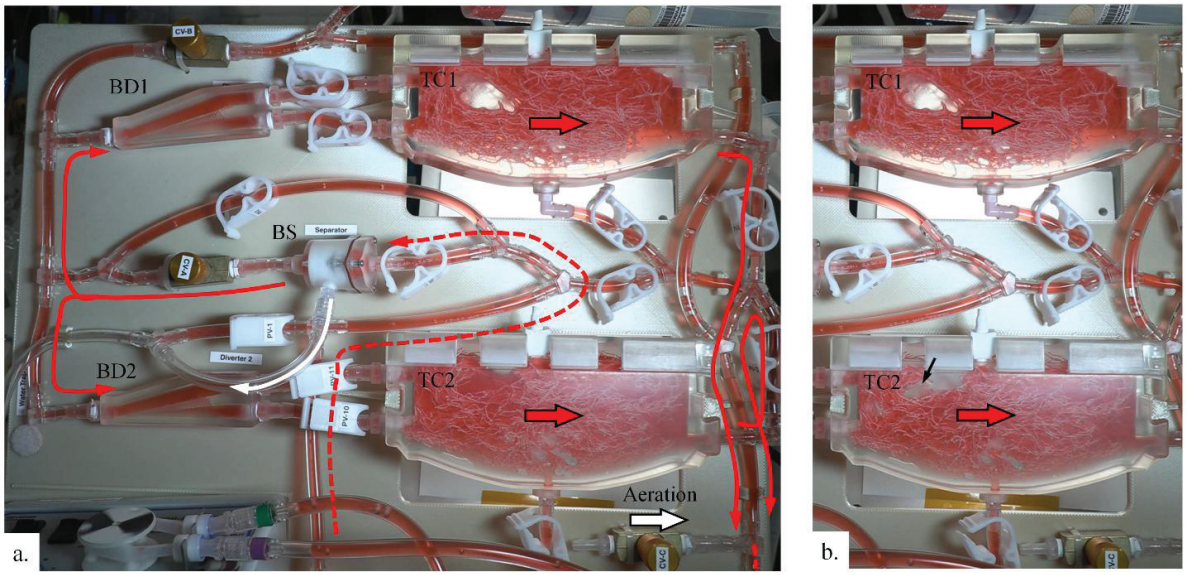


Figure 22. PWM-6 Parallel Hydroponic Flow test with Aeration, BS, BD, and TCs with R4: a. Initiation of Parallel flow and b. fluid distribution 5 min. later identifying fluid shift from TC2 (black arrow) to TC1. The shift of fluid is transient in this case, achieving a steady state in b. with the capillary and hydrodynamic pressures balancing without further fluid shifts detected over the next 25 min.

I. Passive Reservoirs

With successful > 90 min demonstrations of passive reservoirs during PWM 3 & 4 operations[3], less emphasis was assigned to passive reservoir demonstration during PWM 5 & 6. In Figure 24, passive reservoir injection into the loop of PWM-5 is demonstrated. We note that Res1 and Res2 for PWM-5 and PWM-6 do not contain Rayon wicks assuring that capillary connection is maintained between the reservoirs and the loop. The PWM-5 approach is not concerned with capillary connect since an occluding meniscus is certain to form in the reservoir guaranteeing drainage without a concern for ingested bubbles, because the PWM 5 & 6 system are insensitive to bubbles. With Reservoir Stop Cock valves SC1 and ST2 open, in this test the reservoirs are engaged in parallel by first slightly cracking CV-D injecting Res1 contents into the loop at a slow rate, and 7 min later opening CV-E to the degree the drain rate in Res2 overtakes that of Res 1 and is fully drained within 2 min. Res1 continues to drain at a constant rate during the process. Such demonstrations show that special capillary connection is not needed for such no-moving-parts passive reservoirs, and that such reservoirs may be employed in parallel to deliver water, condensate, nutrient, and/or other solutions at varied desired rates to the PWM loop through simple valve control. Optical, acoustic, or conductivity sensors may be employed to gage reservoir fill level. Highly varied rigid or flexible bag reservoir geometries are easily accommodated with concerns of rogue bubbles relegated to second order do to the nature phase separating capability of the PWM loop. (i.e., BS, BD, TC with Root Geometry).

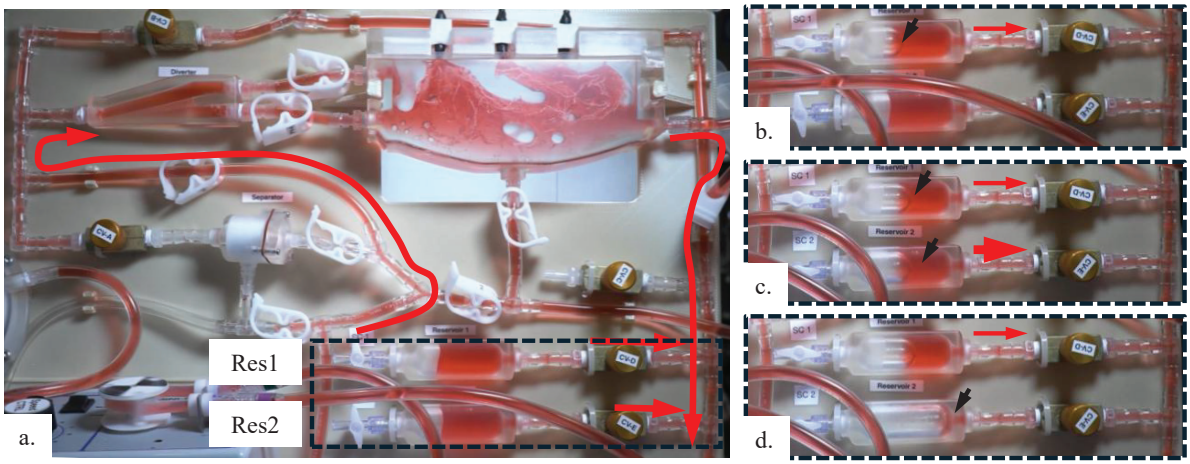


Figure 23. a. PWM-5 passive Reservoir demonstrations: b. CV-D opened slightly drawing meniscus down injecting liquid into loop from Res1 (black arrow). c. 7 min later open CV-E opened significantly drawing Res2 meniscus down quickly injecting liquid into loop from Res2, while Res1 continues to flow (black arrows). d. Res2 drains completely in 2 min and CV-E is closed, while Res1 continues to inject liquid into loop.

J. Performance Limits and Regimes Maps: TC, Aerator, Fittings, BD, BS, WT, and AIS

This section is only partially completed at the time of the submission of this report. It is expected to appear in a subsequent publication.

K. Diagnostics

In Situ Pump Calibration and Flowrate. Whenever the pump head is visible within the video camera FOV, the pump flowrate Q_{pump} may be calculated by measuring the pump head rotation rate ω (Hz) and multiplying by a linear pump calibration coefficient, C_{pump}. As illustrated in Fig. 24a, transient pixel intensity within an AOI of the pump head during flight operations is digitized producing signals such as Fig. 24b with FFT shown in Fig. 24c clearly identifying the pump head rotation rate for each test condition achieved in-flight. We note that during the flight operations, pump flowrates Q_{pump} are nominally called out and recorded by the manual and visual positioning of the Pump control dial by the crew (i.e., F4 ≡ Fast Pump Setting with Dial set to 4, or S8 ≡ Slow Pump Setting with Dial set to 8). A still frame of a flow event where an occluding gas slug is identified via red AOI is provided in Fig. 24d. In such relatively rare cases the velocity of the meniscus may be used unequivocally to determine the pump flow rate. After combing the entire PWM-5, -5b, and-6 video archive, ample cases are found where occluding gas slugs may be tracked such that in situ pump calibrations may be effectively completed as shown in Fig. 25e for PWM 5, -5b, and 6. These calibrations are compared to the original terrestrial pump calibration,[15] listed in Appendix A, with C_{pump} = 0.857 mL/cycle for the 3/16" ID pump head tubing. The differences in calibrations are obvious and due to differences in pump head tubing tensions between PWM-5, -5b, and 6. Goodness of fits are > 0.998.

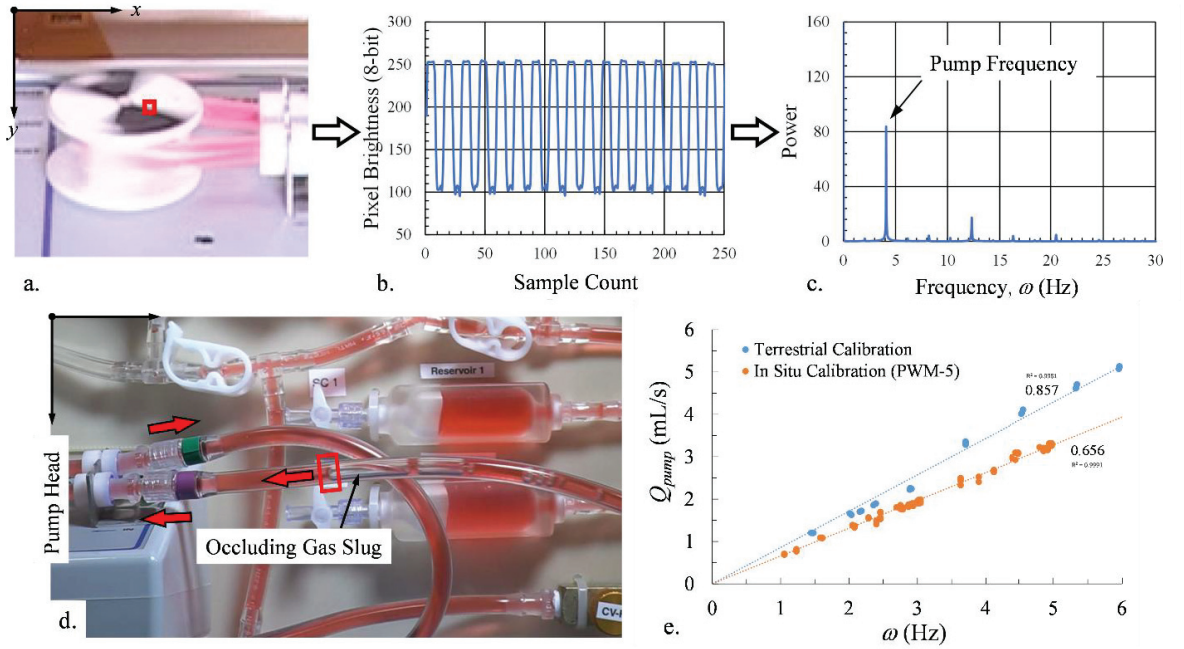


Figure 24. In situ pump calibration: a. still frame image of pump head with red AOI, b. *y*-profile plot of AOI pixel intensity, c. FFT with the pump head frequency identified, d. still frame with red AOI around occluding gas slug upstream of pump head from which advancing meniscus position is digitized and velocity and pump flowrate determined for 3/16" ID tubing. d. In situ calibrations with coefficients for PWM-5, -5b, and -6 compared with original terrestrial calibration.

TC Volume Measurement

To find the approximate instantaneous liquid volume within a given Test Channel, still images are extracted from the video clip of interest at a desired sampling rate (i.e., frames per second). The resulting image stack is thresholded, and several points (typically 30-50) are sampled across the top edge of the binary image to create a series of coordinates corresponding to the location of the free surface. Root model and noted bubble volumes may be subtracted from the result (Ref. Table 2). These values are combined with the known shape of the Wedge or Cylindrical channels to find the fluid cross-sectional area at each location. The array is then integrated numerically using the trapezoidal rule to produce an approximate volume to within ± 5% (worst case), more typically ± 3% for most fill levels. The process is iterated for each image extracted from the video clip establishing the channel volume over time. Due to the resolution of the video files and significant contact angle hysteresis (~20° < θ < ~70°), we assume a flat fluid surface in the crossflow direction. The impact of this assumption is accommodated within the estimated uncertainty of the measurement.

VIII. Brief Discussion: Overall PWM Performance from and Applications Perspective

Careful priming was carried out when time permitted to assure that no air bubbles became entrained in the flow, that liquid slugs were not formed in primarily gas-filled tube section, and that no significant gas volumes were isolated throughout the system tubing. However, with the demonstrated success of the passive phase separating device of the loop, it was found that no special consideration was needed for system priming and that a fast cavalier approach was just as successful as a slow methodical approach because all bubbles would be separated from the flow in a single cycle of the liquid once the pump was turned on.

Non-ideal aspects of the flight hardware included intermittent pump head rotation at low rpm, challenging two phase flow imaging for HD video at high flow rate, the pump head and fittings churning bubbly flows at high speeds, that the video cameras were not always recording such that only HD RTDL video was available during such periods, that on occasion the PVs were not always fully closed (i.e., PWM-6 parallel flow tests and PWM-5b auto prime), and that numerous droplets were ejected from first slot of TC lid during R4 tests with Aeration and BD leading to impaction of ejected droplets on first 3rd of TC SH lid. This latter anticipated observation is highlighted below.

TC Lid. As described above, the underside of the TC lid is lined with a SH screen with the intent to rebound satellite droplets ejected from bubbles bursting along the free surface back to re-coalesce with the free surface. A perforated screen was adopted to enhance visualization of the phenomena. Unfortunately, the fairly low translucency of the screen combined with the small fast satellite droplets permitted not a single observation of the sort envisioned. However, post experiment inspection of the inner lid after tens of thousands of bubble mergers and droplet ejections revealed clear satellite droplet adhesion, coalescence, and growth, as shown in Figure 26. The screen pore size (< 1 mm), estimated satellite droplet diameter (< 1 mm), and satellite droplet velocity (~ $(4\sigma/\rho R)^{1/2}$ ~ 1 m/s), provide evidence supporting how such drops cannot be resolved, are small enough to be trapped in screen perforations, and have ample inertia to penetrate and adhere to the SH surface. Though successful satellite droplet rebounds are certain, we estimate the accumulation of ~ 1.5 mL of ejected liquid adhered to the first 1/3 of the TC Lid near TC entrance. Little to no adhered droplets are observed on the downstream 2/3 of the TC Lid. On the order of ~ 10,000 mL and ~ 100,000 bubbles over a ~ 8 hr period produced this outcome. Mitigations may be pursued to eliminate such droplets, i.e., dab dry and replace lid, employ a non-perforated SH Lid, employ the BS such that no bubbles ever reach the TC, etc.

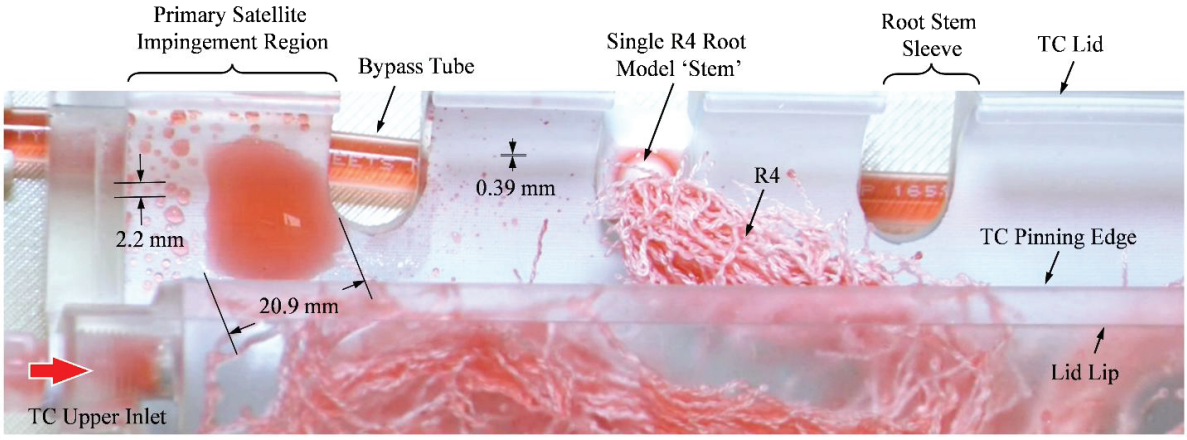


Figure 26. Image of inner TC Lid after PWM-5b Ingestion Limit, Aeration, and Gas Injection tests demonstrating degree of ejected satellite droplet adhesion.

Plant Insertion Changeout. To insert a 'plant,' the channel is partially drained, and the plant model is inserted. The channel is then refilled and run at a variety of fluid levels and pump speeds. A variety of fill levels, bubble injections, fluid accumulations, and liquid and gas bubble separations are achieved within the channels. At the conclusion of runs with a particular plant model, the channel is drained, and the plant model is gently though easily removed. Of note here is that, despite the wetting nature of the roots, nearly all liquid remains attached to the channel as the plant model is removed, reducing the potential for free droplets during subsequent plant manipulations.

IX. Summary

PWM 5 & 6 established numerous positive aspects of Ebb and Flow and Hydroponic plant watering methods in low-g. The microgravity demonstrations employ plumbing elements that exploit the near absence of body forces to achieve passive bubbly flow aeration, bubble separation, gas diversion, bubble mergers and migration, droplet capture, nutrient/water delivery, and the use of plant root geometry for complete microgravity fluid phase separations at different stages of growth. Practical demonstrations of system priming, start-up, shut-down, draining, plant installation, and plant changeout are demonstrated. Such advances offer a variety of plug-and-play solutions for effective plant watering in low- and variable-gravity environments, despite the challenging wetting properties of contaminated aqueous nutrient solutions. From a plant watering systems engineering perspective, practical concerns associated with long duration operation, aeration targets, test channel lid detail, in-channel germination, and system sanitation need should be quantified in the process of system requirements definition.

The demonstrations reported herein are highly likely to find cross-cutting applications in the microgravity environment aboard future spacecraft for life support, propulsion, thermal systems and more.

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Appendix

A. Original terrestrial pump calibration data circa January 18, 2017. (Pump ID in inches)

Table B1. PWM peristaltic pump flowrates in mL/s for all PWM pump head tubing IDs.

Pump Setting / Tube ID	S6	S8	S10	F0	F2	F4	F6	F8	F10
1/16	0.184 ± 0.0006	0.231 ± 0.0007	0.262 ± 0.0012	0.238 ± 0.0007	0.306 ± 0.0016	0.389± 0.0005	0.473 ± 0.0008	0.556 ± 0.0016	0.606 ± 0.0007
3/32	0.448 ± 0.081	0.549 ± 0.006	0.621 ± 0.005	0.563 ± 0.007	0.740 ± 0.005	0.960 ± 0.008	1.17 ± 0.006	1.39 ± 0.004	1.52 ± 0.003
3/16	**1.19 ± 0.006**	**1.65 ± 0.011**	**1.90 ± 0.018**	**1.74 ± 0.018**	**2.26 ± 0.015**	**3.37 ± 0.033**	**4.10 ± 0.033**	**4.70 ± 0.028**	**5.13 ± 0.024**
1/4	2.55 ± 0.192	3.11 ± 0.074	3.55 ± 0.070	3.27 ± 0.066	4.15 ± 0.055	5.26 ± 0.053	6.25 ± 0.066	7.57 ± 0.050	8.33 ± 0.052

Table B2. Volume per rotation calculated from all PWM pump head tubing IDs.

Tube ID	1/16	3/32	3/16	1/4
Volume per rotation (mL/rot)	0.100	0.254	**0.857**	1.43

B. Examples of PWM 5 & 6 Archive use.

Finding a test

Example 1: Find E&F test using Overview sheet.

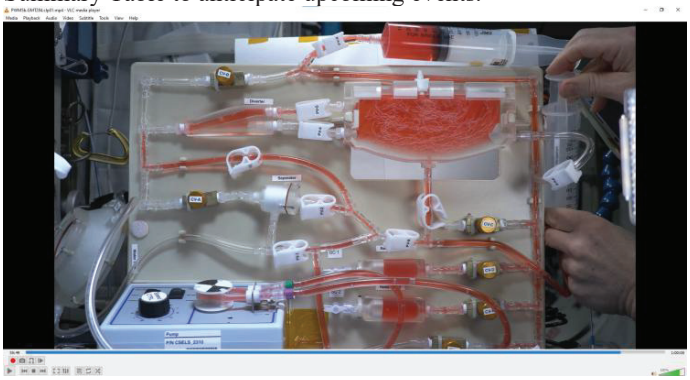
1. Navigate to the Overview sheet in the Operations Summary Table spreadsheet.
2. Scroll to PWM 5b and find Test #4: "E&F TC Base - R4."

94						PWM 5b
95	#	Day	GMT	Activity	Start Time	Notes
96	1	1	284	HW Ready and Fluid Prep	8:34:46	
97	2	1	284	System Priming	9:48:04	Attempts to use pump to "auto-prime" system. Limited success since pump need
98	3	1	284	Dry TC Prime	10:16:03	
99	4	1	284	E&F TC Base - R4	10:23:39	Demonstrates E&F repeatability. (4 ebbs and 3 flows)
100	5	1	284	E&F TC Outlet - R4	10:37:15	Demonstrates repeatability of alternate, less-effective E&F location. (4 ebbs and
101	6	1	284	Hydroponic Flow - R4	11:04:15	
102	7	1	284	Hydro Flow w/ Aer - R4	11:45:25	Gives close-up footage of BD. Special focus on BD performance at different Q and
103		1	284	Stop for Break 1	12:31:05	Stops main recording
104	8	1	284	Hydro Flow w/ Aer - R4 (Resumed)	12:59:11	Gives close-up footage of BD. Special focus on BD performance at different Q and
105	9	1	284	Hydro Flow w/ Aer, BS - R4	14:36:48	Gives close-up footage of BS. Tested at extreme Qg. Liquid penetrates BS during t
106	10	1	284	Investigate BS liquid penetration	16:34:50	Attempts are made to draw liquid out of BS.
107	11	1	284	Hydro Flow w/ AIS - R4	17:03:19	Gives close-up footage of BD. Includes long duration bubble trains, pulsing trains,
108		1	284	Stop for Break 2	17:32:09	Stops both recordings
109	12	1	284	E&F Spot Check TC Base - R4	17:44:50	Demonstrates sustained repeatability after day of testing. Gives close-up view of
110	13	1	284	E&F Spot Check TC Outlet - R4	18:00:30	Demonstrates sustained repeatability at alternate location after day of testing. Gi
111	14	1	284	E&F Spot Check TC Base - R4 (Continued)	18:10:25	Demonstrates sustained repeatability after day of testing. Gives close-up view of
112	15	1	284	Prep HW for Overnight	18:14:26	
113						
114	16	2	285	Hardware Ready	7:40:53	
115	17	2	285	Ingestion Limits - R4	7:58:38	Finds minimum TC volume at different pump speeds. Uses BS to remove gas whe
116	18	2	285	Root Install - R1	8:38:01	
117	19	2	285	Ingestion Limits - R1	8:54:52	Finds minimum TC volume at different pump speeds. Uses BS to remove gas whe
118	20	2	285	E&F TC Base - R1	9:29:38	Demonstrates E&F repeatability. (5 ebbs and flows)
119	21	2	285	E&F TC Outlet - R1	10:04:31	Demonstrates alternate. less-effective E&F location. (2 ebbs and flows)

3. Select the hyperlinked Start Time to enter the Summary Table and jump to GMT:284:10:23:39.

	A	B	C	D	E	F	G	H	I
1	PWM	GMT		Clip	Clip Time	Video Links		Crew	Test
2	##	ddd	hh:mm:ss	##	mm:ss	Main	OTS	Member	
3									
2216	5b	284	10:22:37	1	54:47	Clip1	Clip1	Michael	Dry TC Prime
2217	5b	284	10:23:39	1	55:49	Clip1	Clip1	Michael	E&F TC Base - R4
2218	5b	284	10:25:03	1	57:13	Clip1	Clip1	Michael	E&F TC Base - R4
2219	5b	284	10:25:45	1	57:55	Clip1	Clip1	Michael	E&F TC Base - R4
2220	5b	284	10:26:52	1	59:02	Clip1	Clip1	Michael	E&F TC Base - R4
2221	5b	284	10:27:21	1	59:31	Clip1	Clip1	Michael	E&F TC Base - R4
2222	5b	284	10:28:42	2	00:52	Clip2	Clip2	Michael	E&F TC Base - R4
2223	5b	284	10:29:34	2	01:44	Clip2	Clip2	Michael	E&F TC Base - R4
2224	5b	284	10:30:47	2	02:57	Clip2	Clip2	Michael	E&F TC Base - R4
2225	5b	284	10:31:17	2	03:27	Clip2	Clip2	Michael	E&F TC Base - R4
2226	5b	284	10:31:35	2	03:45	Clip2	Clip2	Michael	E&F TC Base - R4
2227	5b	284	10:32:53	2	05:03	Clip2	Clip2	Michael	E&F TC Base - R4
2228	5b	284	10:33:28	2	05:38	Clip2	Clip2	Michael	E&F TC Base - R4
2229	5b	284	10:34:31	2	06:41	Clip2	Clip2	Michael	E&F TC Base - R4
2230	5b	284	10:35:09	2	07:19	Clip2	Clip2	Michael	E&F TC Base - R4
2231	5b	284	10:36:33	2	08:43	Clip2	Clip2	Michael	E&F TC Base - R4

4. Select the Main or OTS video link and navigate to clip time 55:49 to see the test performed. Reference Summary Table to anticipate upcoming events.

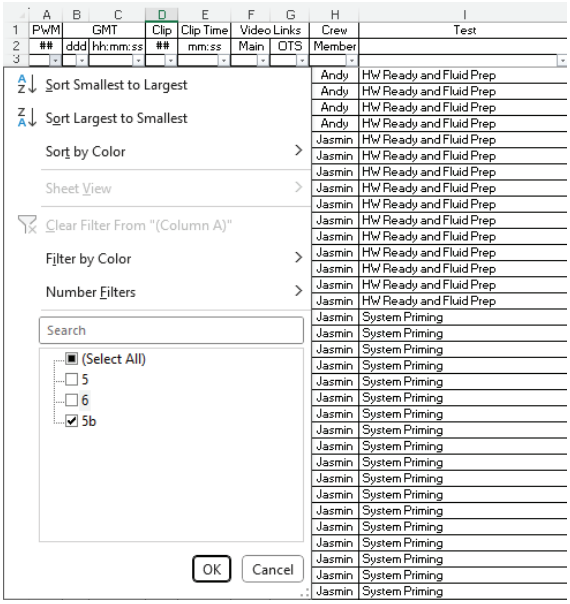


Example 2: Find E&F test using Summary Table filters.

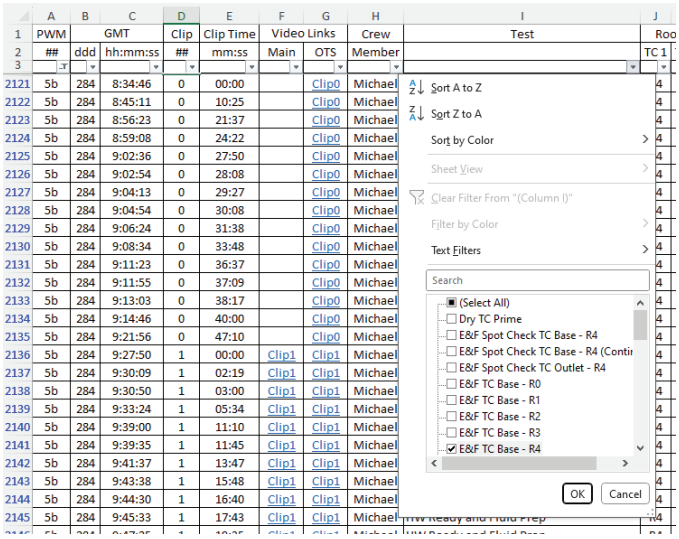
1. Navigate to the PWM_Summary_Table sheet in the Operations Summary Table spreadsheet.
2. Ensure filters are activated in Row 3. If drop-down arrows do not appear in Row 3, select the row and use (Ctrl+ Shift + L) to reactivate the filters.

	A	B	C	D	E	F	G	H	I	J
1	PWM	GMT		Clip	Clip Time	Video Links		Crew	Test	Rc
2	##	ddd	hh:mm:ss	##	mm:ss	Main	OTS	Member		TC 1
3										
4	5	017	8:14:55	1	00:00	Clip1	Clip1	Andy	HW Ready and Fluid Prep	R4
5	5	017	8:16:00	1	01:05	Clip1	Clip1	Andy	HW Ready and Fluid Prep	R4
6	5	017	8:26:15	1	11:20	Clip1	Clip1	Andy	HW Ready and Fluid Prep	R4
7	5	017	10:35:47	3	20:46	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
8	5	017	10:37:55	3	22:54	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
9	5	017	10:43:06	3	28:05	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
10	5	017	10:43:24	3	28:23	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
11	5	017	10:45:29	3	30:28	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
12	5	017	10:49:22	3	34:21	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
13	5	017	10:50:43	3	35:42	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
14	5	017	10:51:28	3	36:27	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
15	5	017	10:53:08	3	38:07	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
16	5	017	10:54:38	3	39:37	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
17	5	017	11:01:38	3	46:37	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
18	5	017	11:05:58	3	50:57	Clip3	Clip3	Jasmin	System Priming	R4

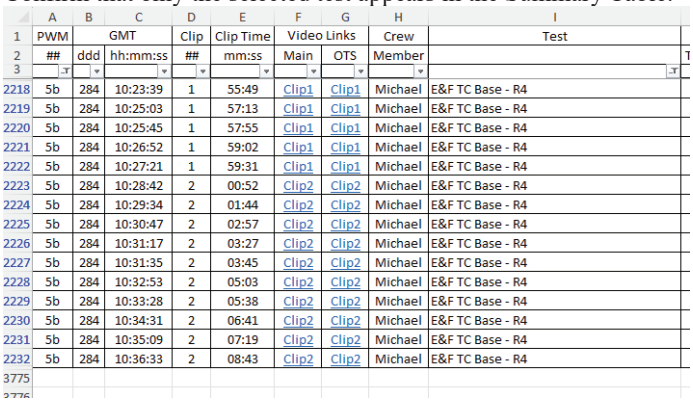
3. Select the drop-down arrow in cell A3 to filter by PWM experiment. Uncheck 5 and 6 leaving only 5b checked. Select OK.



4. Select the drop-down arrow in cell I3 to filter by test name. Uncheck (Select All) and check “E&F TC Base - R4.” Select OK.

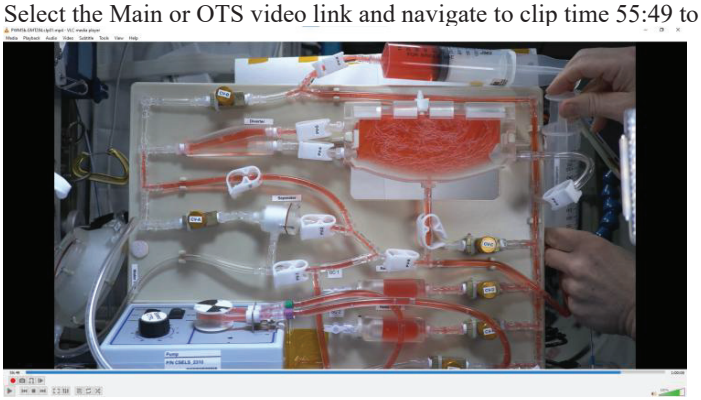


5. Confirm that only the selected test appears in the Summary Table.



	A	B	C	D	E	F	G	H	I
1	PWM		GMT	Clip	Clip Time	Video Links		Crew	Test
2	##	ddd	hh:mm:ss	##	mm:ss	Main	OTS	Member	
2218	5b	284	10:23:39	1	55:49	Clip1	Clip1	Michael	E&F TC Base - R4
2219	5b	284	10:25:03	1	57:13	Clip1	Clip1	Michael	E&F TC Base - R4
2220	5b	284	10:25:45	1	57:55	Clip1	Clip1	Michael	E&F TC Base - R4
2221	5b	284	10:26:52	1	59:02	Clip1	Clip1	Michael	E&F TC Base - R4
2222	5b	284	10:27:21	1	59:31	Clip1	Clip1	Michael	E&F TC Base - R4
2223	5b	284	10:28:42	2	00:52	Clip2	Clip2	Michael	E&F TC Base - R4
2224	5b	284	10:29:34	2	01:44	Clip2	Clip2	Michael	E&F TC Base - R4
2225	5b	284	10:30:47	2	02:57	Clip2	Clip2	Michael	E&F TC Base - R4
2226	5b	284	10:31:17	2	03:27	Clip2	Clip2	Michael	E&F TC Base - R4
2227	5b	284	10:31:35	2	03:45	Clip2	Clip2	Michael	E&F TC Base - R4
2228	5b	284	10:32:53	2	05:03	Clip2	Clip2	Michael	E&F TC Base - R4
2229	5b	284	10:33:28	2	05:38	Clip2	Clip2	Michael	E&F TC Base - R4
2230	5b	284	10:34:31	2	06:41	Clip2	Clip2	Michael	E&F TC Base - R4
2231	5b	284	10:35:09	2	07:19	Clip2	Clip2	Michael	E&F TC Base - R4
2232	5b	284	10:36:33	2	08:43	Clip2	Clip2	Michael	E&F TC Base - R4
3775									

6. Select the Main or OTS video link and navigate to clip time 55:49 to see the test performed.



7. To remove filters, select “Clear Filter From…” under each drop down arrow or use Home > Editing > Sort & Filter > Clear.

Filtering for an event

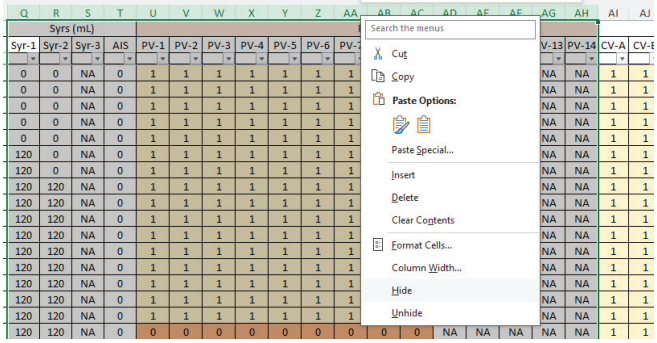
Example 3: Filter for aeration at max pump speed.

1. Navigate to the PWM_Summary_Table sheet in the Operations Summary Table spreadsheet.

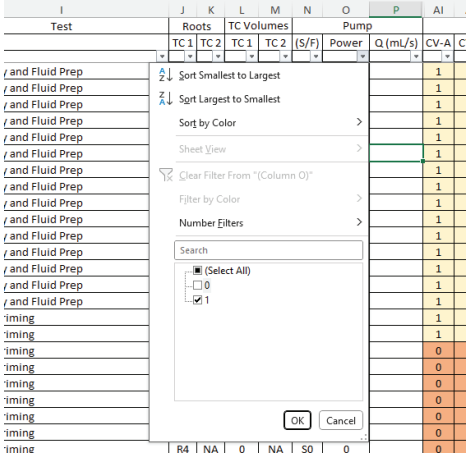
2. Ensure filters are activated in Row 3. If drop-down arrows do not appear in Row 3, select the row and use (Ctrl+ Shift + L) to reactivate the filters.

	A	B	C	D	E	F	G	H	I	J
1	PWM	GMT		Clip	Clip Time	Video Links		Crew	Test	Rc
2	##	ddd	hh:mm:ss	##	mm:ss	Main	OTS	Member		TC 1
3										
4	5	017	8:14:55	1	00:00	Clip1	Clip1	Andy	HW Ready and Fluid Prep	R4
5	5	017	8:16:00	1	01:05	Clip1	Clip1	Andy	HW Ready and Fluid Prep	R4
6	5	017	8:26:15	1	11:20	Clip1	Clip1	Andy	HW Ready and Fluid Prep	R4
7	5	017	10:35:47	3	20:46	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
8	5	017	10:37:55	3	22:54	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
9	5	017	10:43:06	3	28:05	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
10	5	017	10:43:24	3	28:23	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
11	5	017	10:45:29	3	30:28	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
12	5	017	10:49:22	3	34:21	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
13	5	017	10:50:43	3	35:42	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
14	5	017	10:51:28	3	36:27	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
15	5	017	10:53:08	3	38:07	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
16	5	017	10:54:38	3	39:37	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
17	5	017	11:01:38	3	46:37	Clip3	Clip3	Jasmin	HW Ready and Fluid Prep	R4
18	5	017	11:05:58	3	50:57	Clip3	Clip3	Jasmin	System Priming	R4

3. Select columns Q through AH. Right click and select “Hide.” (These columns are not relevant to the current inquiry. The columns can be brought back by selecting P through AI and selecting “Unhide.”)



4. Select the drop-down arrow in cell O3 to filter for when the pump is on. Uncheck 0 and select OK.

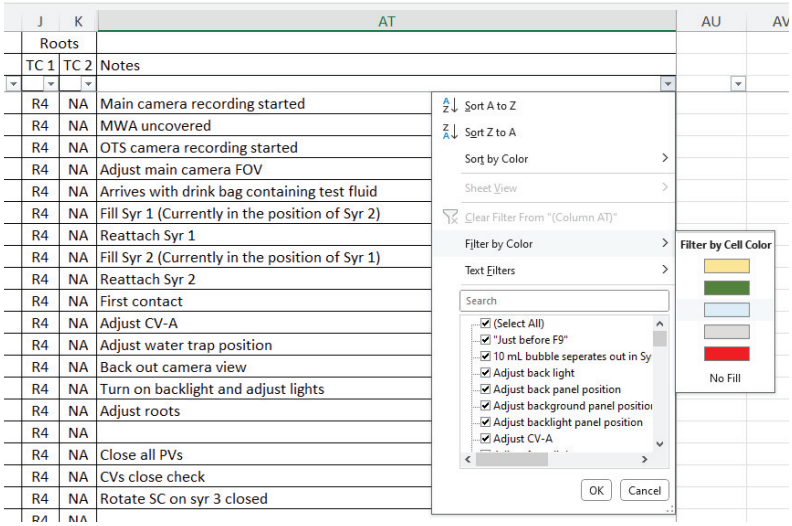


5. Select the drop-down arrow in cell AK3 to filter for when the aerator is on. Uncheck 0 and select OK.
6. Select the drop-down arrow in cell N3 to filter by pump speed. Uncheck “Select All”, check F10, and select OK.
7. There are 50 events recorded at the given pump settings with aeration. Browse events, use video links to view tests, and clear filters when finished.

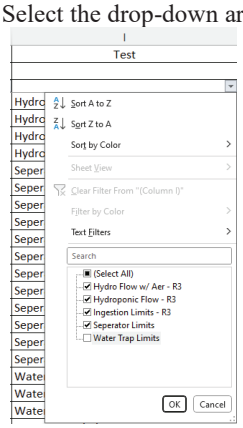
Example 4: Filter for TC ingestion with Root Model 3.

1. Navigate to the PWM_Summary_Table sheet in the Operations Summary Table spreadsheet.
2. Ensure filters are activated in Row 3. If drop-down arrows do not appear in Row 3, select the row and use (Ctrl + Shift + L) to reactivate the filters.
3. Zoom out to 70%.

4. Select columns L through AS. Right click and select “Hide.”
5. Zoom in to 120%.
6. Select the drop-down arrow in cell AT3 and apply Filter by Color > (Blue).



7. Select the drop-down arrow in cell J3 and apply the filter for “R3”.
8. Select the drop-down arrow in cell I3 and uncheck “Water Trap Limits.”



9. 56 instances of ingestion (start and stop) are recorded with Root Model 3.

C. Crew Procedures for PWM-5 (identical to PWM-5b) and PWM-6

Procedure #	Procedure Name
MGUEPWMN018	2.018 PLANT WATER MANAGEMENT 5&6 HARDWARE READY
MGUEPWMN019	2.019 PLANT WATER MANAGEMENT 5 MWA PREP AND HARDWARE SET UP
MGUEPWMN020	2.020 PLANT WATER MANAGEMENT 5 FLUID PREP AND SYSTEM PRIMING
MGUEPWMN021	2.021 PLANT WATER MANAGEMENT 5 EBB AND FLOW
MGUEPWMN022	2.022 PLANT WATER MANAGEMENT 5 HYDROPONIC FLOW
MGUEPWMN023	2.023 PLANT WATER MANAGEMENT 5 SPOT CHECK
MGUEPWMN024	2.024 PLANT WATER MANAGEMENT 5 ROOT TESTS
MGUEPWMN025	2.025 PLANT WATER MANAGEMENT 5 LIMITS TEST
MGUEPWMN026	2.026 PLANT WATER MANAGEMENT 5 TEARDOWN AND STOW
MGUEPWMN027	2.027 PLANT WATER MANAGEMENT 6 MWA PREP AND HARDWARE SET UP
MGUEPWMN028	2.028 PLANT WATER MANAGEMENT 6 FLUID PREP AND SYSTEM PRIMING
MGUEPWMN029	2.029 PLANT WATER MANAGEMENT 6 EBB AND FLOW
MGUEPWMN030	2.030 PLANT WATER MANAGEMENT 6 HYDROPONIC FLOW
MGUEPWMN031	2.031 PLANT WATER MANAGEMENT 6 SPOT CHECK
MGUEPWMN032	2.032 PLANT WATER MANAGEMENT 6 ROOT TESTS
MGUEPWMN033	2.033 PLANT WATER MANAGEMENT 6 LIMITS TEST
MGUEPWMN034	2.034 PLANT WATER MANAGEMENT 6 TEARDOWN AND STOW
MGUEPWMN035	2.035 PLANT WATER MANAGEMENT 5&6 OVERNIGHT SAFING

2.018 PLANT WATER MANAGEMENT 5&6 HARDWARE READY

OBJECTIVE:

To prepare hardware for Plant Water Management 5&6 operations.

MATERIALS:

256GB SD Card (two)

NODE2 Cam 1

1. ✓NODE2 Camcorder set up for live over-the-shoulder downlink of Plant Water Management operations

NODE2 Cam 2

2. ✓Second NODE2 Camcorder set up for close-up view of MWA

3. Install 256GB SD Card (two) into second NODE2 Camcorder with close-up view of MWA.

4. CAMCORDER SETTINGS
   As required, refer to 1.103 XF705 CAMCORDER NOMENCLATURE, all (SODF: PhotoTV: CANON XF705).

   4.1 ✓Lens Cover opened

   4.2 sw POWER → ON

   4.3 ✓LCD (Viewfinder) – '**STBY**' and no waveform type information is displayed

   If no '**STBY**', initialize the 256GB SD Card
   - pb MENU → Press
   - Joystick → Navigate, '**Recording Media/Setup**'
   - Joystick → Navigate, '**Initialize Media**'
   - Joystick → Press
   - Joystick → Press, '**SD Card A(B**')
   - Joystick → Select, '**OK**'
   - Joystick → Press
   - Initializing Progress Message Appears
   - Joystick → Press, '**OK**'
   - pb MENU → Press

   If waveform type information is displayed
   - pb WFM → Press, until the information is no longer displayed

   4.4 ✓LCD (Viewfinder) – '**YCC422 10 bit; 3840x2160**' displayed

   4.5 ✓'**ND 1/XX**' not displayed in LCD or Viewfinder (bottom center location next to f/stop information)

   If '**ND 1/XX**' is displayed
   - pb ND Filter +/- → Press, until '**ND**' is no longer visible

   4.6 sw FOCUS → M

4.7 sw IRIS → M

4.8 ✓sw ZOOM – ROCKER

4.9 ✓sw SHUTTER – OFF

4.10 sw FULL AUTO → OFF

4.11 ✓sw AGC – ON

4.12 ✓sw GAIN – L

4.13 ✓sw AWB – ON

4.14 ✓sw AUDIO CH1 – A, CH2 – A (Located inside the plastic door on the side of Camcorder)

4.15 ✓sw INPUT1 – ANALOG

4.16 ✓sw ANALOG – MIC (Located on a side of Camcorder handle above INPUT1 XLR audio input)

4.17 ✓sw INPUT2 – ANALOG

4.18 ✓sw ANALOG – MIC (Located on a side of INPUT2 XLR audio input on the back of the Camcorder)

NOTE
The Internal Camcorder Microphone will be used to record audio of the pump and water movement.

5. pb MENU → Press
6. Joystick → '**Audio Setup**'
7. Joystick → Press
8. Joystick → '**Select CH1/CH2 Input**'
9. Joystick → Press
10. Joystick → '**Built-in Mic**'
11. Joystick → Press
12. pb MENU → Press

NOD2S4

13. Remove Bungee and Temp stow.
14. Remove CTB and Temp stow.
15. sw LED Work Light (two) → ON
16. ✓**POIC** for FOV

NODE2 Cam 2 17. Begin recording to 256GB SD Card (two) on second NODE2 Camcorder with close-up view of MWA.

Ground should update IMS for the following parts:

Bungee TO: Temp stow (step 13)

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
			Existing procedural hazard controls are not applicable to this procedure.

2.019 PLANT WATER MANAGEMENT 5 MWA PREP AND HARDWARE SET UP

OBJECTIVE:

To set up Node 2 deployed camcorders, install Plant Water Management 5 on MWA, and prep experiment for operations.

TOOLS:

MWA Utility Kit P/N SJG33110310-301:

#10 Fasteners (two)
Camcorder (two)
Multi-Use Bracket (two)
LED Work Light P/N WORKLIGHT-001 (two)
Laptop Desk
Bungee
Flexible Bracket (two)
Work Light USB Power Cable P/N WORKLIGHTCABLE-001 (two)

PARTS:

Plant Water Management 5 P/N PWM5601-01 B/C 00283837W
Pump P/N CSELS_2310
Power Cable P/N CSELS_2320

MATERIALS:

A-4 Printer Paper
Gray Tape
Dry Wipe (as needed)
Cable Tie
Lens Cloth
Kapton Tape
Ziplock Bag

1. HARDWARE MWA INSTALLATION

NODE2 Cam 1

1.1 Set up NODE2 Camcorder for live over-the-shoulder video with FOV of MWA area.

1.2 ✓**POIC** for FOV

Figure 1. Mounting Points

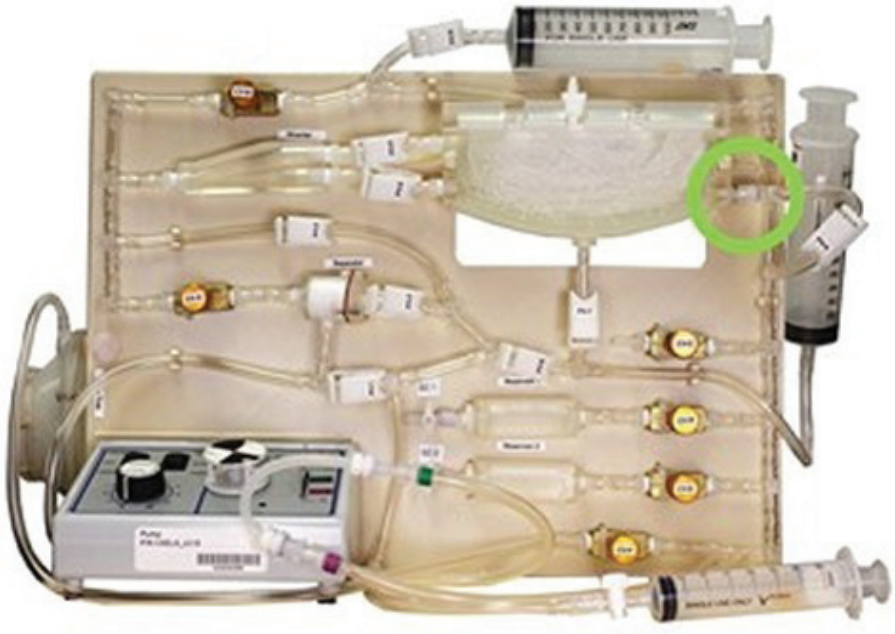


Figure 2. Leur Lock Attachment

NOD2S4

1.3 Use keyhole locations to install Plant Water Management 5 on MWA, leaving approximately 6 to 10 inches space between back of the test stand and the Crew Quarters [#10 Fasteners (two)] (Figure 1).

1.4 Attach leur lock to Test Cell by pushing and turning CW one quarter turn (Figure 2).

1.5 ✓All tubing is connected

```
**********************************************************************************
*
*   If any damage to hardware,
*
*   |  ✓POIC
*
**********************************************************************************
```

2. PUMP INSTALLATION

Figure 3. Pump in the OFF State

Pump

2.1 ✓sw Flow Direction – OFF (rocker switch middle position, Figure 3)

Turn Speed CTRL knob CCW to 0.

2.2 Attach Pump to MWA [Gray Tape] (Figure 2[1]).

NOD2S4

2.3 ✓120 VDC to 120 VAC Inverter SW2 – OFF (S/N 1038)

2.4 Route Power Cable through back of Plant Water Management 5.

Pump →|← Power Cable

2.5 AWS Snowcone Power Supply ←|→ Inverter GFCI Cable 3'

2.6 Coil AWS Snowcone Power Supply. Temp stow.

2.7 Power Cable →|← Inverter GFCI Cable 3’

2.8 ✓Inverter GFCI Cable 3’ →|← 120 VDC to 120 VAC Inverter J2 (S/N 1038)

2.9 sw 120 VDC to 120 VAC Inverter SW2 → ON (S/N 1038)

Inverter GFCI Cable 3'

2.9.1 pb RESET → Press (Green LED)

pb TEST → Press

Verify RESET pops out

If RESET does not pop out or LED not illuminated,

- sw 120 VDC to 120 VAC Inverter SW2 → OFF (S/N 1038)
- Repeat step 2.9 and step 2.9.1
- If second attempt fails,
  - Replace Inverter GFCI Cable 3'
  - Report S/N or B/C to **POIC**

pb RESET → Press (Green LED)

3. PUMP FUNCTIONAL TEST

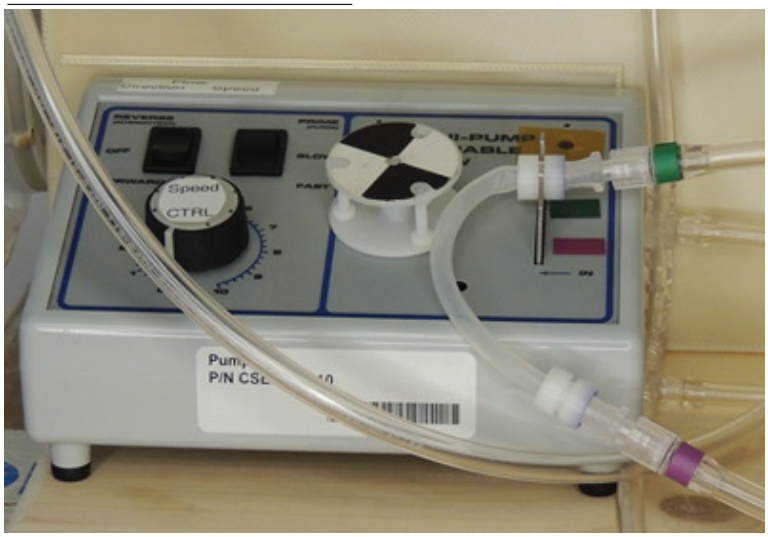


Figure 4. Pump Tubing Disconnected

3.1 ✓Pump head tubing removed from pump head (Figure 4)

3.2 sw Flow Speed → SLOW (rocker switch middle position)

3.3 Turn Speed CTRL knob to 8.

3.4 sw Flow Direction → FORWARD (rocker switch bottom position)

3.5 While pump is on, turn Speed CTRL knob CW to 10.
Verify pump speed increases.

3.6 sw Flow Direction → OFF (rocker switch middle position)

3.7 Turn Speed CTRL knob to 0.

4. LIGHTING AND CAMCORDER SETUP

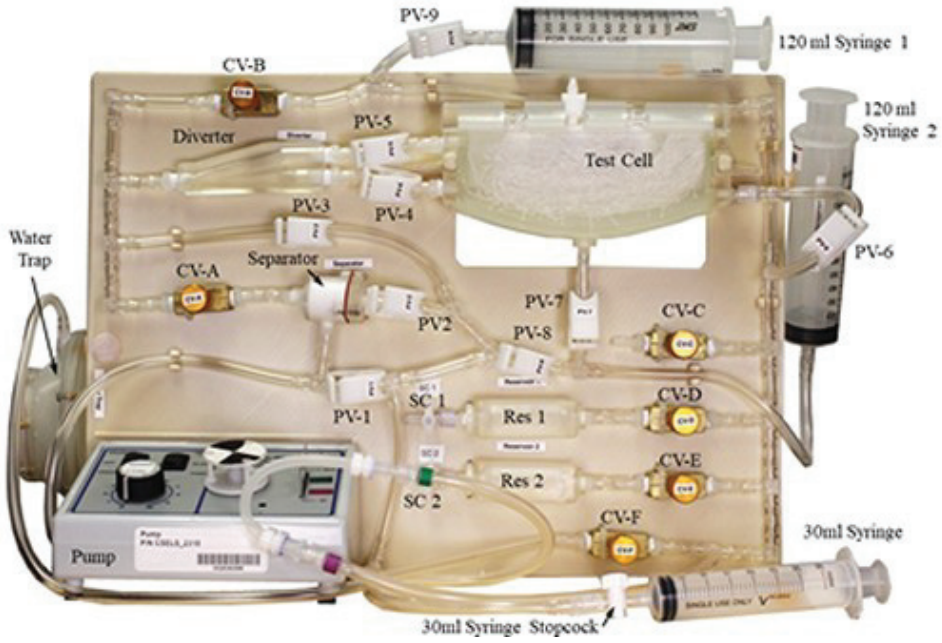


Figure 5. Hardware Configuration

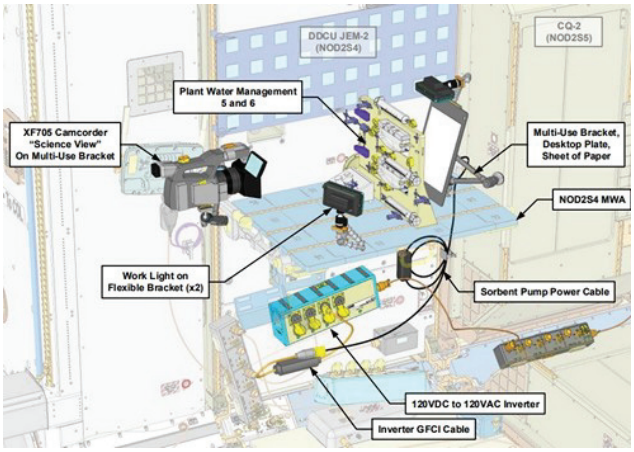


Figure 6. MWA Setup

4.1 ✓Plant Water Management 5 matches Figure 5

4.2 Attach Multi-Use Bracket to Seat Track behind Plant Water Management 5 (Figure 6).

4.3 Attach Laptop Desk to Multi-Use Bracket behind Plant Water Management 5 (Figure 6).

4.4 Secure A-4 Printer Paper (portrait orientation) on Laptop Desk [Kapton Tape].

4.5 Attach Flexible Bracket to Seat Track behind Plant Water Management 5 (Figure 6[2]).

4.6 Attach second Flexible Bracket to Seat Track in front of Plant Water Management 5 (Figure 6[3]).

4.7 Mount LED Work Light (two) to Flexible Bracket (two).

4.8 ✓Multi-Port USB Charger →|← Inverter GFCI Cable 3'

4.9 If Multi-Port USB Charger not present,

4.9.1 ✓**MCC-H** for Multi-Port USB Charger and Inverter GFCI Cable 3' stowage location

4.9.2 ✓sw 120 VDC to 120 VAC Inverter SW3 – OFF (S/N 1038)

4.9.3 Multi-Port USB Charger →|← Inverter GFCI Cable 3'

4.9.4 Inverter GFCI Cable 3' →|← 120 VDC to 120 VAC Inverter J3

4.9.5 sw 120 VDC to 120 VAC Inverter SW3 → ON (S/N 1038)

Inverter GFCI Cable 3'

4.9.6 pb RESET → Press (Green LED)

pb TEST → Press

Verify RESET pops out

If RESET does not pop out or LED not illuminated,

sw 120 VDC to 120 VAC Inverter SW3 → OFF (S/N 1038)

Repeat step 2.9 and step 2.9.1

If second attempt fails,

Replace Inverter GFCI Cable 3'

Report S/N or B/C to **POIC**

pb RESET → Press (Green LED)

4.10 Work Light USB Power Cable (two) →|← LED Work Light (two)

4.11 Work Light USB Power Cable (two) →|← Multi-Port USB Charger

4.12 sw LED Work Light (two) → ON

NOTE

1. Camcorder to be mounted on a Multi-Use Bracket about 3 1/2 feet from the Crew Quarters. Camcorder should NOT be mounted directly to MWA. The Camcorder needs to provide an independent record of motion to avoid loss of science data.
2. The face of the lens of the Camcorder needs to be at least three feet (36 inches) from the front face of Plant Water Management 5 to ensure the ability to focus and reduce lensing effects such as fisheye.

4.13 Attach Multi-Use Bracket to Seat Track.

NODE2 Cam 2

4.14 Attach second NODE2 Camcorder to Multi-Use Bracket.

4.15 Set up second NODE2 Camcorder for live downlink with close-up view of MWA (Figure 6[4]).

4.16 ✓**POIC** for FOV and LED Work Light adjustments

4.17 Clean Camcorder lens as needed for best video imagery [Lens Cloth].

5. OVERNIGHT SAFING

5.1 sw 120 VDC to 120 VAC Inverter SW2 → OFF (S/N 1038)

5.2 Secure the Inverter GFCI Cable 3' to Inverter Switch Guard at SW2 and SW3 [Cable Tie] (if required, allow for a bend radius of approximately 1.5 in). Refer to 3.104 120 VDC TO 120 VAC INVERTER/GFCI OPERATIONAL CONSTRAINTS (US SODF: CSS: 3. Plug-In Plans: 3.1 Reference)

5.3 sw LED Work Light (two) → OFF

5.4 Place 2.0 CTB over hardware on MWA and secure with Bungee.

✓Plant Water Management 5 and Pump are covered

NODE2 Camcorder

5.5 sw POWER (two) → OFF

5.6 Stow per Stowage Note.

Ground should update IMS for the following parts:
Bungee TO: installed (step 5.4)
Plant Water Management 5 B/C 00283837W TO: installed (step 1.3)
Pump P/N CSELS_2310 TO: installed (step 2.2)
Power Cable P/N CSELS_2320 TO: installed (step 2.7)
Multi-Use Bracket TO: installed (step 4.2)
LED Work Light TO: installed (step 4.7)
Inverter GFCI Cable 3' TO: installed (step 2.7)
Laptop Desk TO: installed (step 4.3)

Flexible Bracket (two) TO: installed (step 4.5)
Work Light USB Power Cable P/N WORKLIGHTCABLE-001 (two) TO: installed (step 4.11)

Referenced Images

1)

2)

3)

4)

2.020 PLANT WATER MANAGEMENT 5 FLUID PREP AND SYSTEM PRIMING

OBJECTIVE:

To prime Plant Water Management 5 in preparation for experimentation.

MATERIALS:

Dry Wipe (as needed)
Ziplock Bag
Beverage BOB:
Tropical Punch Drink Bag
Beverage Straw Assembly

TOOLS:

Hands-free VOX

NOTE
1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

1. TEST FLUID TRANSFER TO TEST STAND KIT

PWD

1.1 Fill Tropical Punch Drink Bag at PWD.

1.2 Shake Tropical Punch Drink Bag vigorously.

Temp stow for five minutes for particles to dissolve.

MWA

1.3 View Liquid Transfer video (01:09).

1.4 Temp stow Dry Wipes near MWA.

1.5 Demate Plant Water Management 120ml Syringe (Syringe 1) from tubing.

1.6 Mate Beverage Straw Assembly to Syringe 1 [Dry Wipe].

1.7 Mate Tropical Punch Drink Bag to Beverage Straw Assembly [Dry Wipe].

1.8 Open clamp on Beverage Straw Assembly and draw 120ml of fluid into Syringe 1. Close clamp on Beverage Straw Assembly [Dry Wipe].

1.9 If air bubbles are drawn into syringe from the bag,

Demate Syringe 1 from Beverage Straw Assembly.

~

Use centrifugal force method to push air toward the tip of the syringe.

Dispense air into a Dry Wipe.

Repeat fill from bag and centrifuge method until syringe has at least 110ml of bubble-free fluid (bubbles less than 1mm in diameter are okay).

1.10 Demate Syringe 1 from Beverage Straw Assembly [Dry Wipe].

1.11 Mate Syringe 1 to tubing and then mount to Plant Water Management 5 with attached Velcro [Dry Wipe].

1.12 Repeat step 1.5 to step 1.11 for Syringe 2.

1.13 Temp stow Beverage Straw Assembly and Tropical Punch Drink Bag.

1.14 Place used Dry Wipes in Ziplock Bag and discard.

2. TUBING, RESERVOIRS, AND TEST CELL PRIME

NOTE

1. Obstruction-free, close-up Camcorder view should be maintained during experiment.
2. When priming to TEE fitting, liquid should only be moved until flush with the junction so that the other legs of the TEE fitting are not occluded.

2.1 ✓VOX configured for sound for hands-free communication

2.2 ✓**POIC** to ensure proper configuration before priming

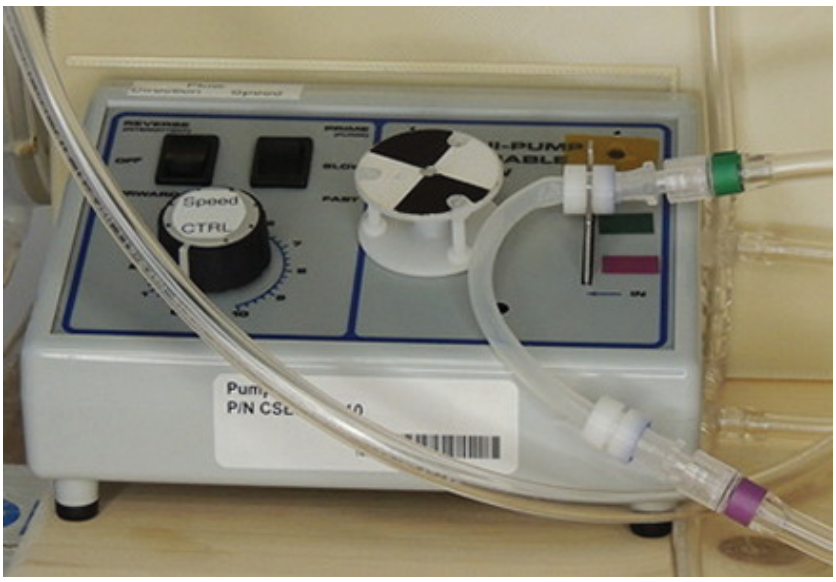


Figure 1. Pump Hose Unconnected

2.3 Ensure Pump Hose is disconnected from Pump Head (Figure 1).

2.4 ✓All valves are closed

2.5 Open PV-7.

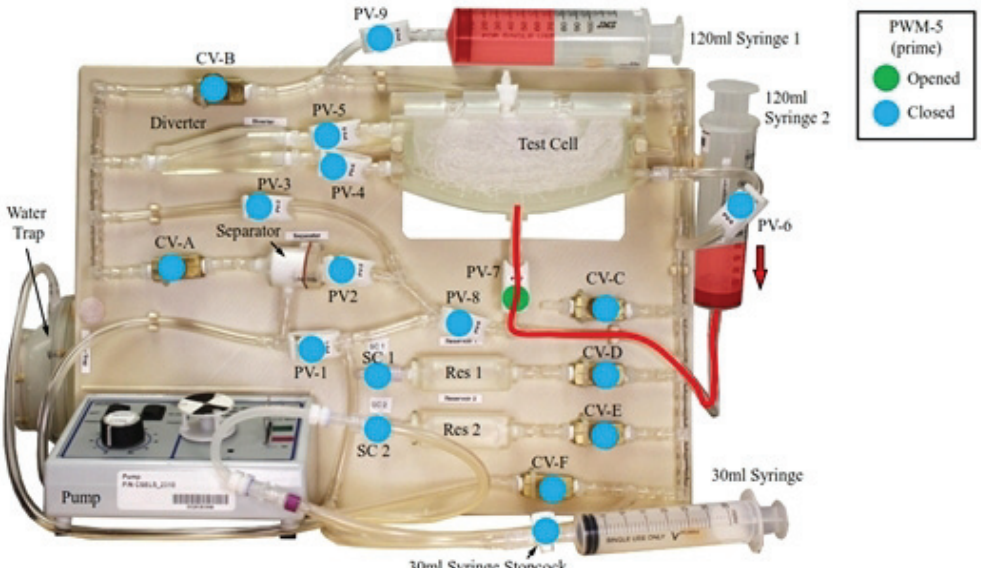


Figure 2. Prime to Bottom of Test Cell

2.6 Using Syringe 2, prime tubing through PV-7 until flush with bottom of Test Cell (Figure 2).

2.7 Close PV-7.

2.8 Open PV-8 and PV-1.

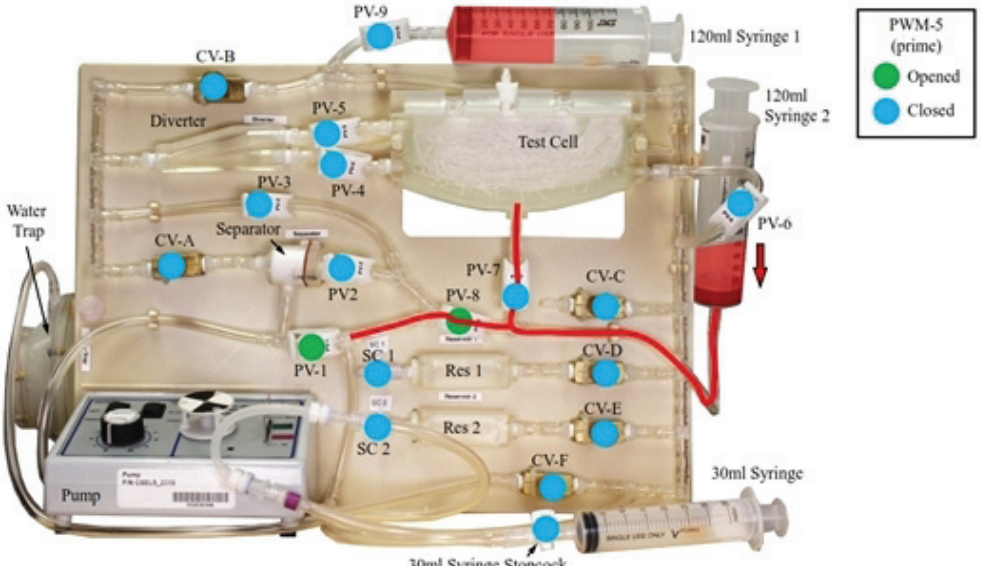


Figure 3. Prime to TEE fitting before PV-1

2.9 Using the Syringe 2, prime tubing through PV-8 to the TEE fitting just before PV-1 (Figure 3).

2.10 Close PV-1.

2.11 Open PV-2.

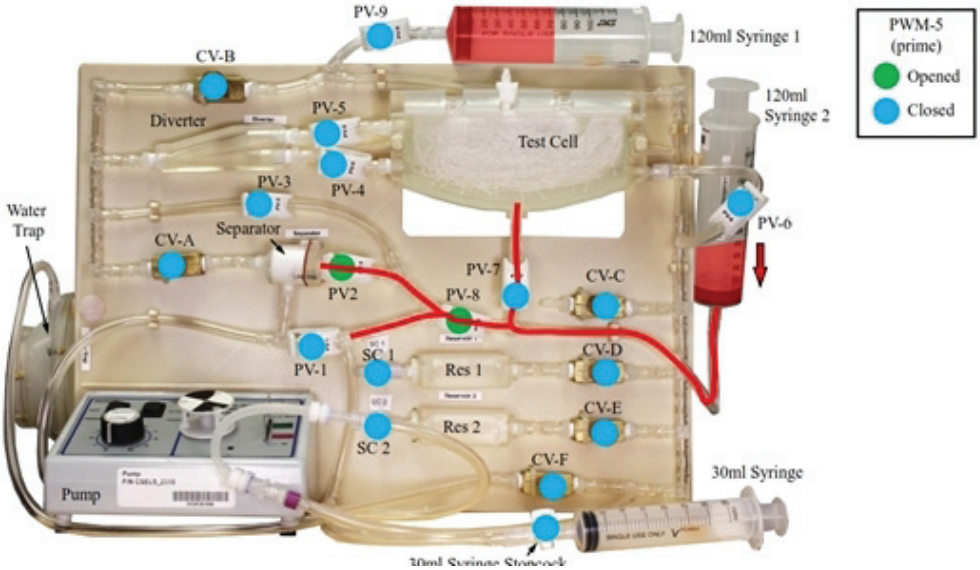


Figure 4. Prime to Separator Entrance

2.12 Using the Syringe 2, prime tubing through PV-2 and up to the entrance of the Separator (Figure 4).

2.13 Close PV-2.

2.14 Open CV-A to full stop and PV-3.

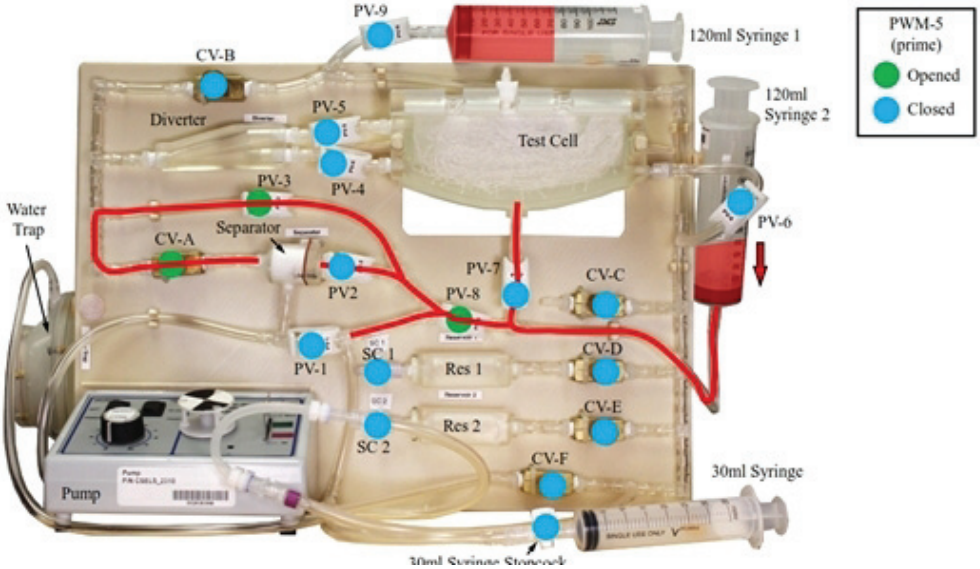


Figure 5. Prime to Separator Exit

2.15 Using Syringe 2, prime tubing through CV-A and up to the exit of the Separator (Figure 5).

2.16 Close CV-A.

2.17 Open PV-5.

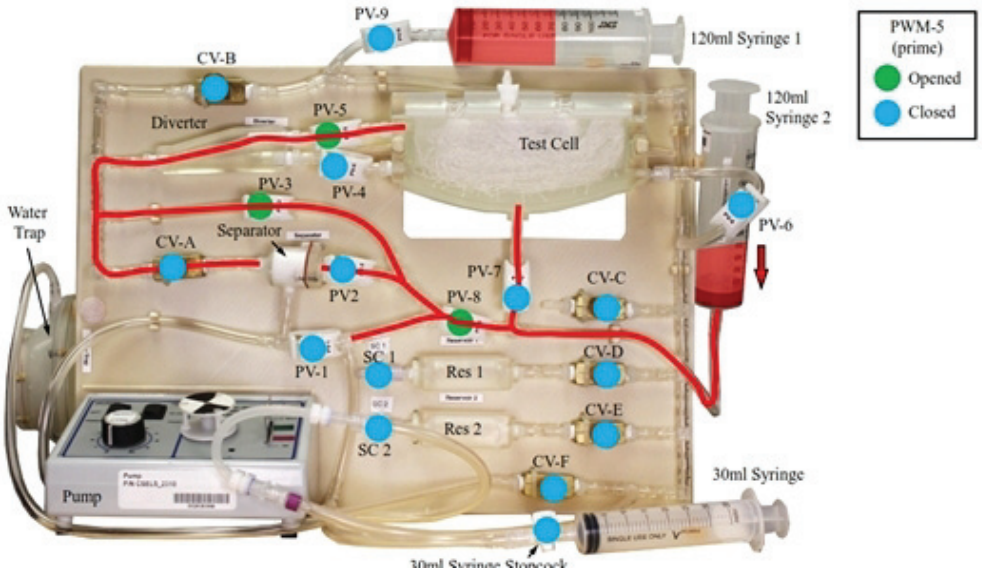


Figure 6. Prime through PV-5 to Test Cell

2.18 Using Syringe 2, prime tubing through PV-5 until flush with entrance to Test Cell (Figure 6).

2.19 Close PV-5.

2.20 Open PV-4.

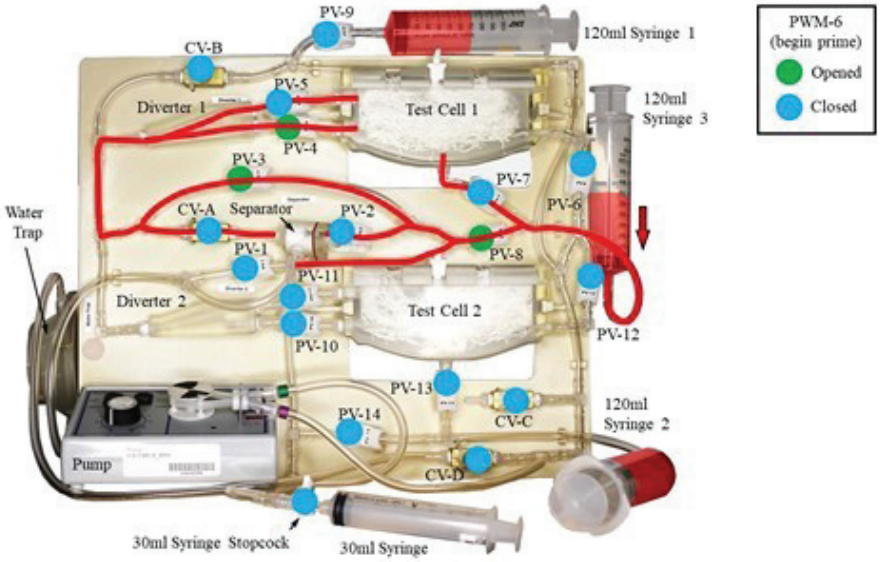


Figure 7. Prime through PV-4 to Test Cell

2.21 Using Syringe 2, prime tubing through PV-4 until flush with entrance to Test Cell (Figure 7).

2.22 Close PV-4.

2.23 Open CV-B to full stop and PV-6.

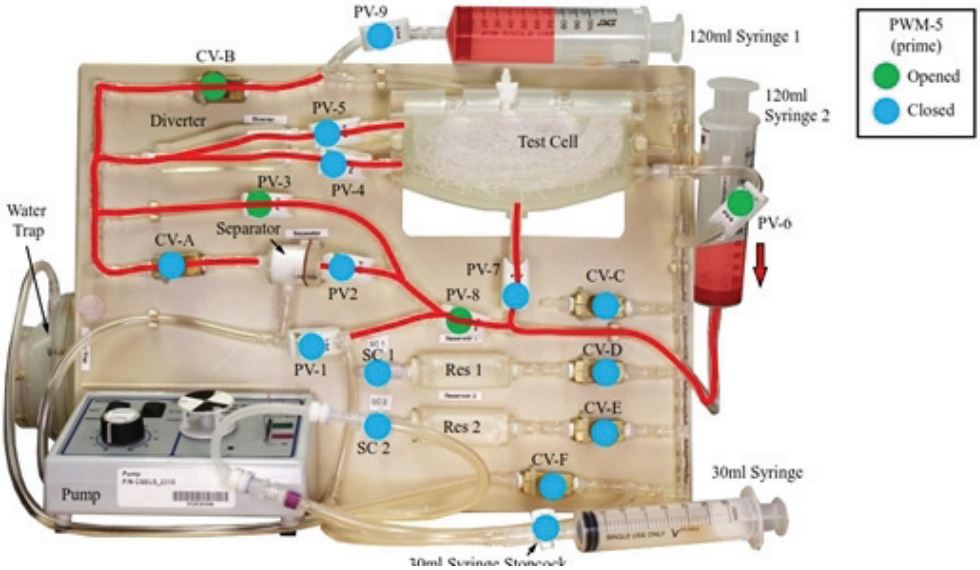


Figure 8. Prime to Y-fitting

2.24 Using Syringe 2, prime tubing through CV-B and up to the Y-fitting (Figure 8).

2.25 Close CV-B, PV-6, PV-3, and PV-8.

2.26 Open CV-F to full stop and PV-9.

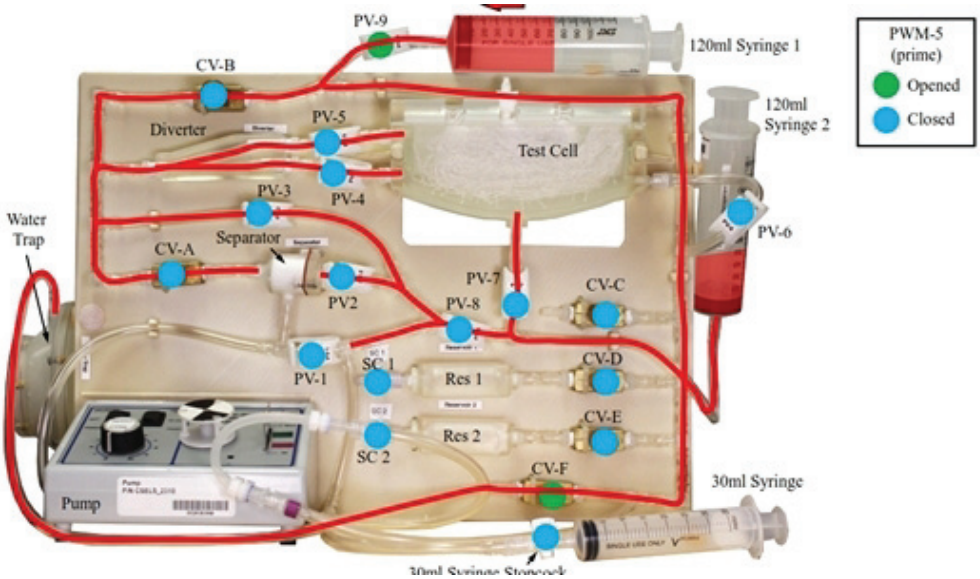


Figure 9. Prime to Water Trap

2.27 Using Syringe 1, prime tubing through CV-F until flush with Water Trap connector (Figure 9).

2.28 Close CV-F.

2.29 Open PV-1.

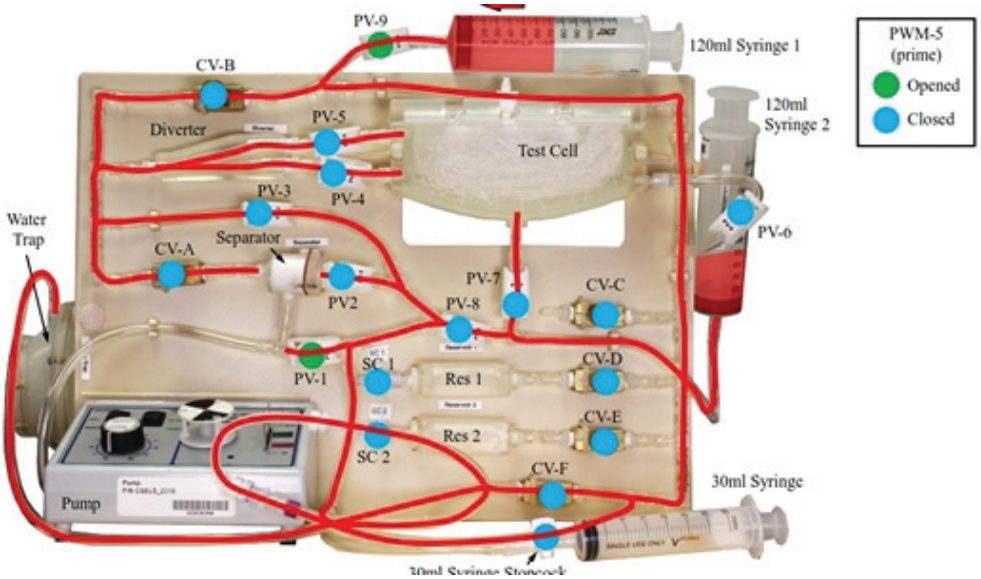


Figure 10. Prime to TEE fitting past PV-1

2.30 Using Syringe 1, prime tubing through PV-1, and stop at TEE fitting just downstream of PV-1 (Figure 10).

2.31 Close PV-1.

2.32 Open CV-E to full stop and SC-2 (handle parallel to tubing).

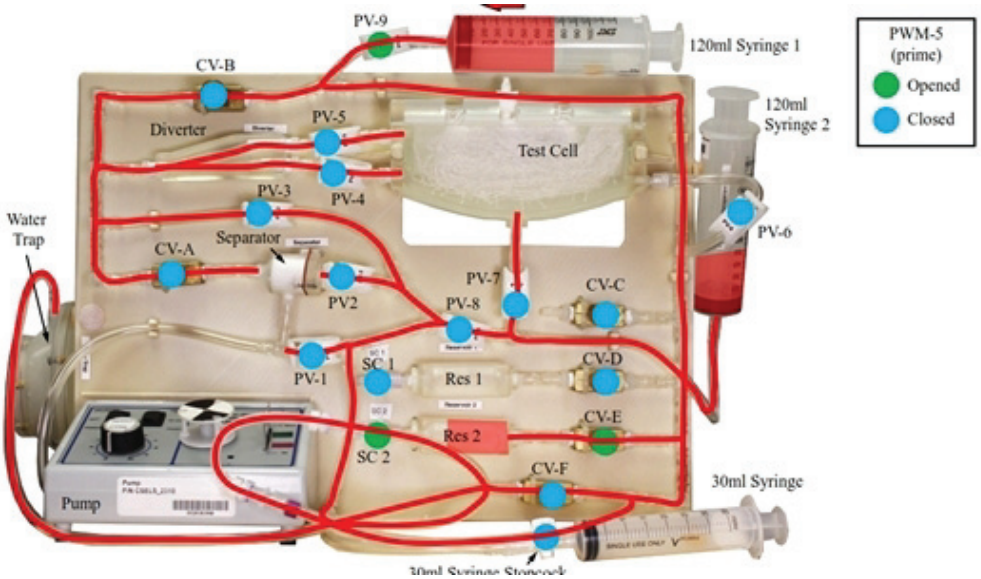


Figure 11. Prime Reservoir 2

2.33 Using Syringe 1, prime Reservoir 2 to approximately 75 percent full (Figure 11).

2.34 Close CV-E and SC-2 (handle perpendicular to tubing).

2.35 Open CV-D to full stop and SC-1 (handle parallel to tubing).

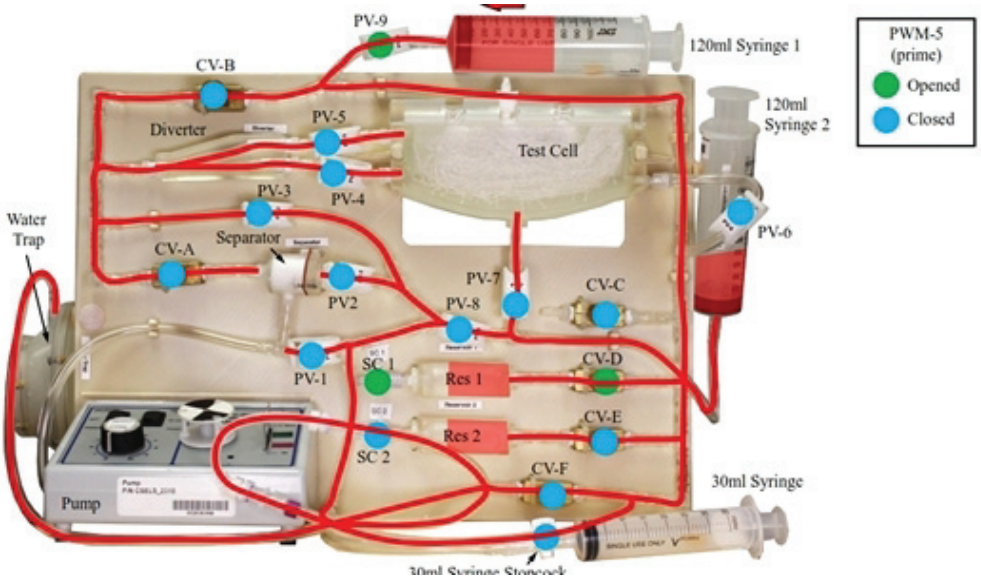


Figure 12. Prime Reservoir 1

2.36 Using Syringe 1, prime Reservoir 1 to approximately 75 percent full (Figure 12).

2.37 Close CV-D and SC-1 (handle perpendicular to tubing).

2.38 Open PV-6.

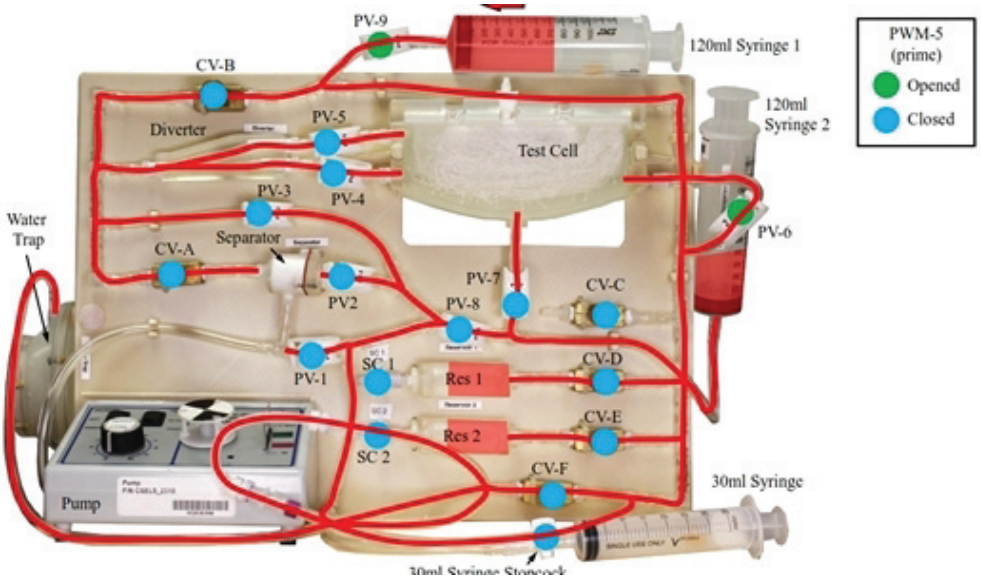


Figure 13. Prime to Test Cell Exit Port

2.39 Using Syringe 1, prime tubing through PV-6 until flush with Test Cell exit port (Figure 13).

2.40 Close PV-6 and PV-9.

2.41 ✓**POIC** to confirm tube priming complete

3. TEST CELL PRIME

3.1 Open PV-7.

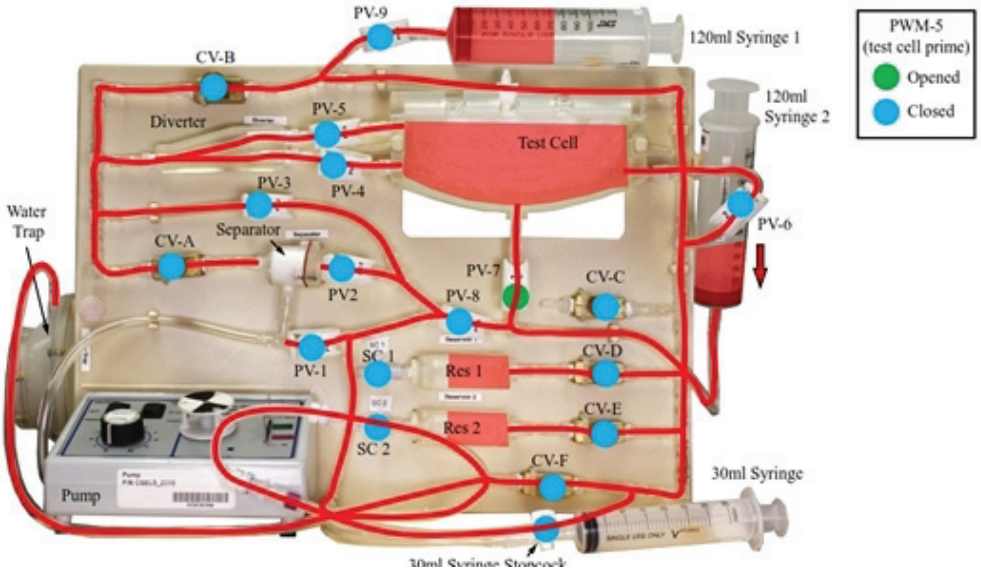


Figure 14. Prime Test Cell

3.2 Using Syringe 2, slowly prime Test Cell, attempting to deliver the highest stable liquid volume possible with a single plunge, adjusting plunge rate as necessary (Figure 14).

3.3 Close PV-7.

3.4 ✓**POIC** for Test Cell fill level

If instructed,

3.4.1 Open PV-8, PV-9, PV-3, PV-4, and PV-6.

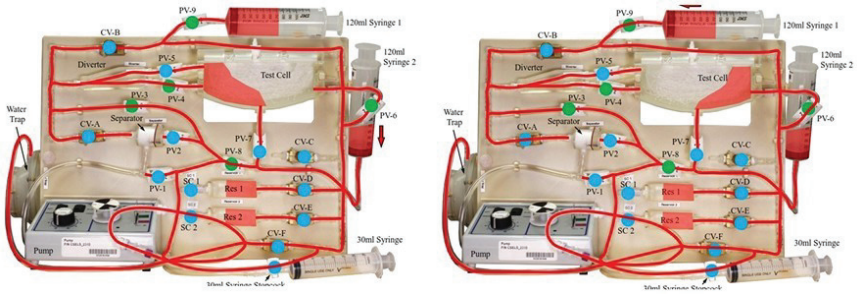


Figure 15. (a) Prime Test Cell Inlet / (b) Prime Test Cell Outlet

~

3.4.2 Using Syringe 2, slowly prime Test Cell inlet from left (Figure 15a).

3.4.3 Using Syringe 1, slowly prime Test Cell outlet from right (Figure 15b).

3.4.4 Close PV-8, PV-9, PV-3, PV-4, and PV-6.

3.5 ✓**POIC** to confirm Test Cell priming complete

OBJECTIVE:

To add and remove liquid from Plant Water Management 5 Test Cell using various methods.

NOTE
1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA 1. EBB AND FLOW FROM TEST CELL BASE

1.1 ✓VOX configured for sound for hands-free communication

1.2 ✓Plant Water Management 120ml Syringe (two) tick marks are in FOV

1.3 **On POIC GO**

Open PV-7.

✓All other valves are closed

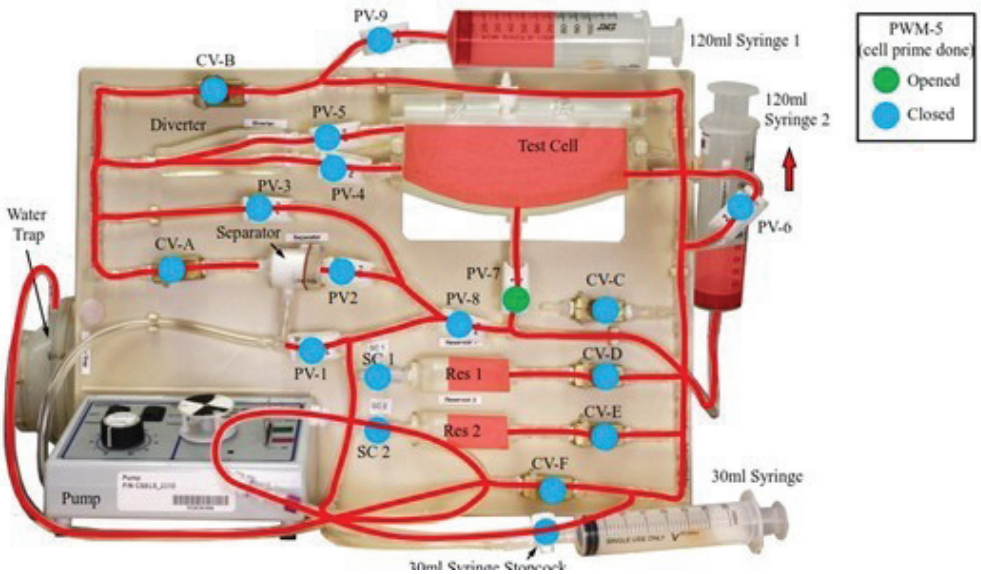


Figure 1. Ebb from Test Cell Base

1.4 Using Syringe 2, slowly withdraw as much liquid from Test Cell as possible without ingesting bubbles (Figure 1).

1.5 Using Syringe 2, slowly depress plunger to refill Test Cell with as much liquid as possible to just below pinning edge without introducing bubbles.

1.6 Repeat step 1.4 and step 1.5 four more times.

1.7 Close PV-7.

2. EBB AND FLOW FROM TEST CELL INLET

2.1 **On POIC GO**

Open PV-8, PV-3, PV-4, PV-6, and PV-9.

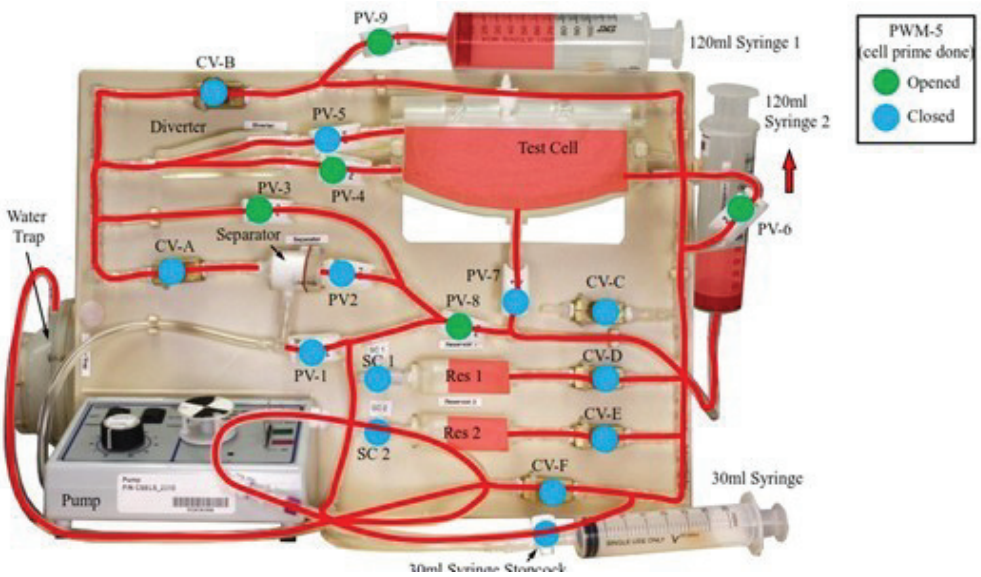


Figure 2. Ebb from Test Cell Inlet

2.2 Using Syringe 2, slowly withdraw as much liquid from Test Cell inlet as possible without ingesting bubbles (Figure 2).

2.3 Using Syringe 2, slowly depress plunger to refill Test Cell inlet with as much liquid as possible to just below pinning edge without introducing bubbles.

2.4 Repeat step 2.2 and step 2.3.

3. EBB AND FLOW FROM TEST CELL OUTLET

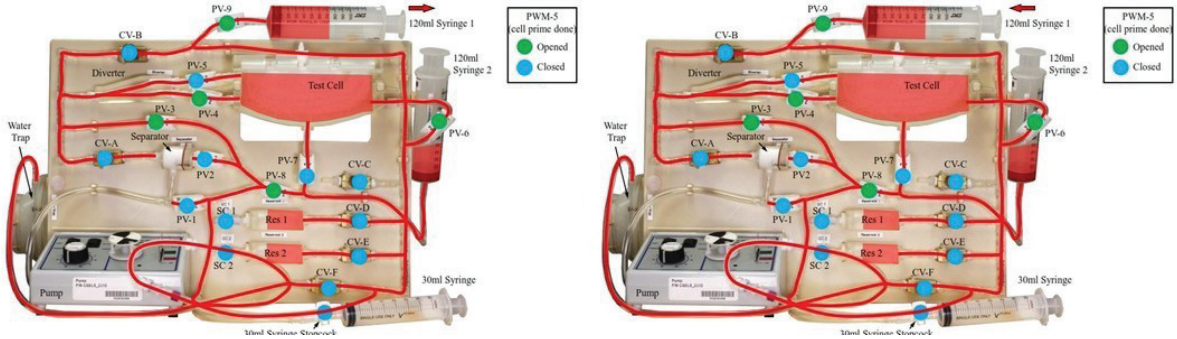


Figure 3. (a) Ebb from Test Cell Outlet / (b) Flow from Test Cell Outlet

3.1 Using Syringe 1, slowly withdraw as much liquid as possible from Test Cell oulet without ingesting bubbles (Figure 3a).

3.2 Using Syringe 1, slowly depress plunger to refill Test Cell outlet with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 3b).

3.3 Repeat step 3.1 and step 3.2.

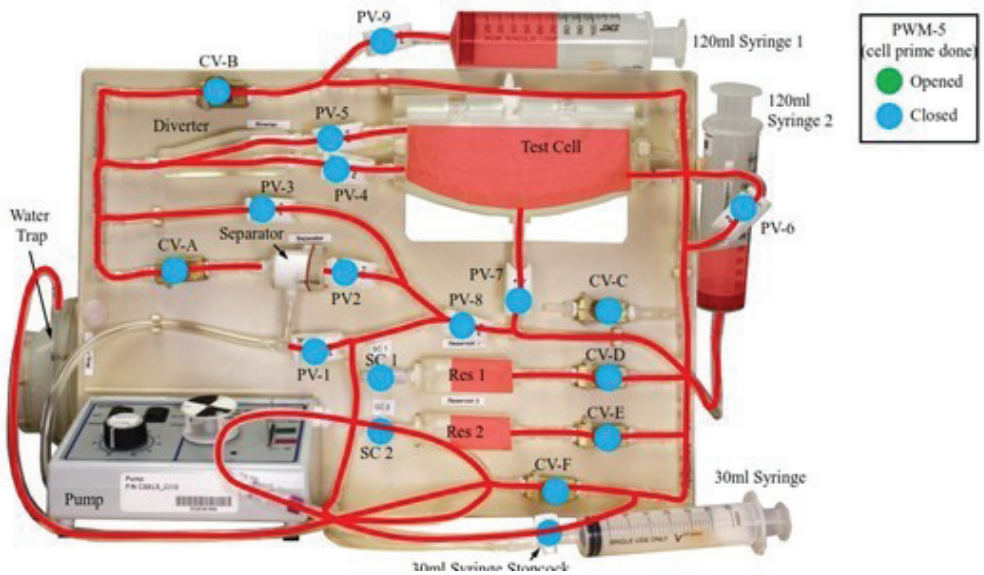


Figure 4. All PVs Closed

3.4 Close PV-8, PV-3, PV-4, PV-6, and PV-9 (Figure 4).

3.5 ✓**POIC** to report Syringe 1 and Syringe 2 volumes

OBJECTIVE:

To test various forms of hydroponic flow throughout the Plant Water Management 5 system.

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA 1. HYDROPONIC FLOW WITHOUT BUBBLES

1.1 ✓VOX configured for sound for hands-free communication

1.2 ✓Plant Water Management 120ml Syringe (two) tick marks are in FOV

1.3 sw 120 VDC to 120 VAC Inverter SW2 → ON

1.4 Attach pump head tubing to pump head. Refer to Pump Tubing (00:16).

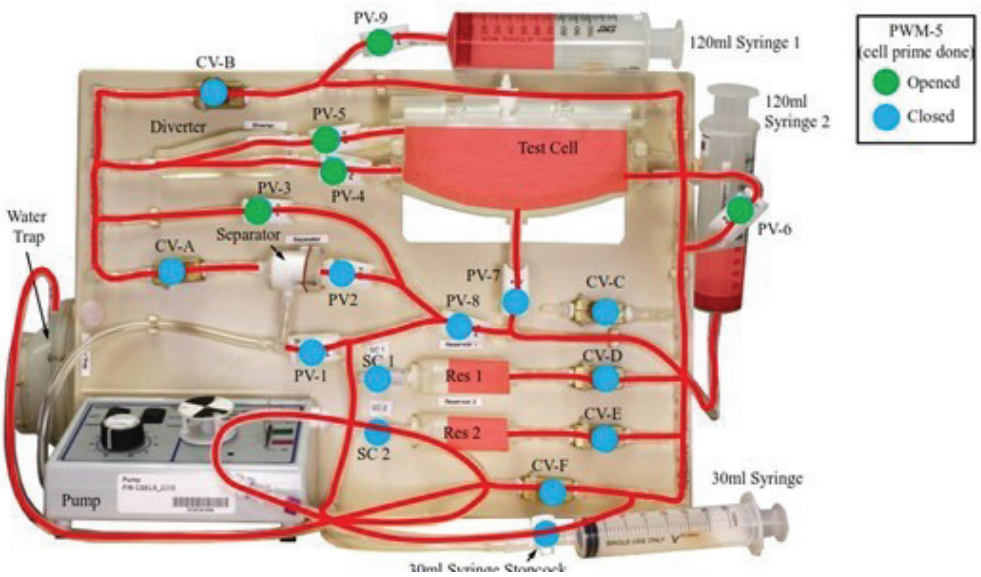


Figure 1. Flow without Bubbles

1.5 Open PV-3, PV-4, PV-5, PV-6, and PV-9 (Figure 1).

1.6 ✓All other valves are closed

1.7 sw Flow Speed → SLOW (rocker switch middle position)

1.8 Turn Speed CTRL knob to 5.

1.9 sw Flow Direction → FORWARD (rocker switch bottom position)

1.10 Monitor hydroponic flow (approximately 20 minutes).

Adjust Speed CTRL knob as directed by **POIC**.

1.11 **On POIC GO**

Turn Speed CTRL knob CW, increasing by increments of 1, as instructed.

1.12 sw Flow Direction → OFF (rocker switch middle position)

1.13 **On POIC GO**

Using Syringe 1, slowly add/remove liquid to Test Cell, as instructed.

1.14 ✓sw Flow Speed – SLOW (rocker switch middle position)

1.15 Turn Speed CTRL knob to 5.

1.16 sw Flow Direction → FORWARD (rocker switch bottom position)

1.17 **On POIC GO**

Turn Speed CTRL knob CW, increasing by increments of 1, as instructed.

1.18 sw Flow Direction → OFF (rocker switch middle position)

1.19 Repeat step 1.13 to step 1.18.

2. HYDROPONIC FLOW WITH AERATION

2.1 ✓sw Flow Speed – SLOW (rocker switch middle position)

2.2 Turn Speed CTRL knob to 5.

2.3 sw Flow Direction → FORWARD (rocker switch bottom position)

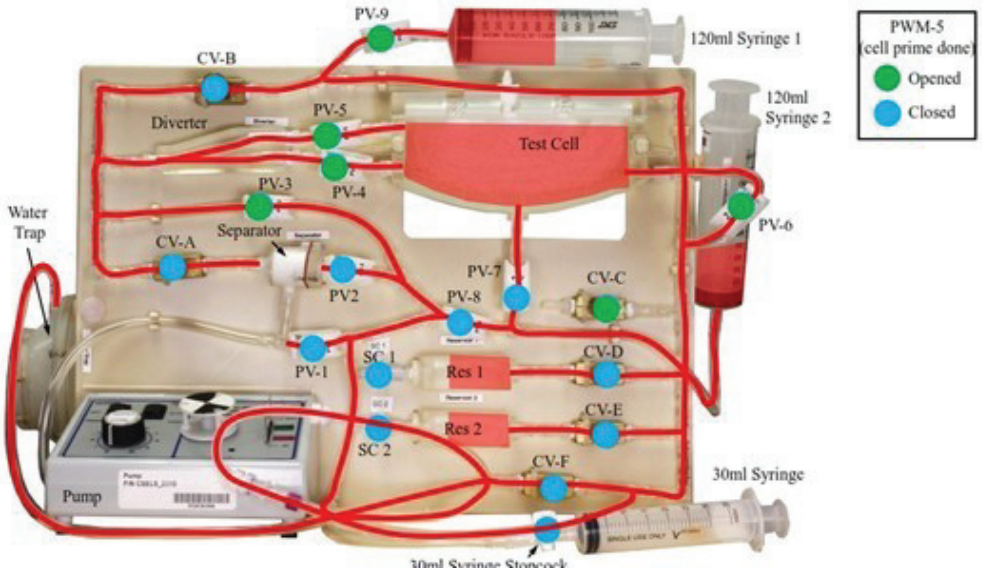


Figure 2. CV-C Open

2.4 Slowly open CV-C by turning knob CCW until bubbles are just visible and ingested into system (Figure 2).

2.5 ✓**POIC** for adjustments to CV-C and/or Pump

Observe bubble management of Diverter and Test Cell.

2.6 ✓**POIC** to add/remove liquid from Test Cell as instructed

2.7 Repeat step 2.5 and step 2.6 twice.

2.8 sw Flow Direction → OFF (rocker switch middle position)

2.9 ✓**POIC** to add/remove liquid from Test Cell as instructed

3. AERATION, SEPARATION, AND WATER TRAP

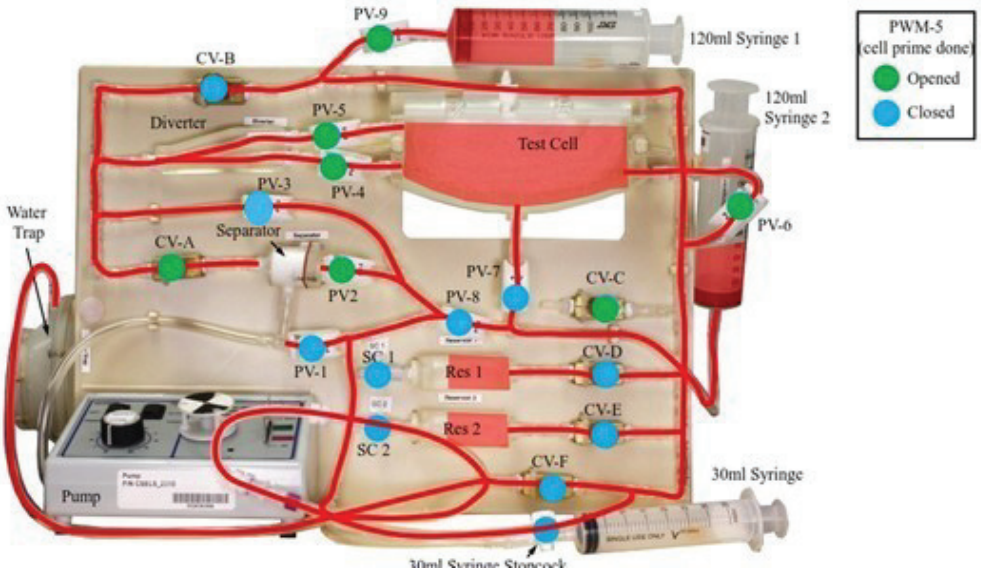


Figure 3. Aeration, Separation, and Water Trap

3.1 Open PV-2 and open CV-A to full stop (Figure 3).

Close PV-3.

3.2 ✓PV-4, PV-5, PV-6, PV-9 and CV-C – OPEN (Figure 3)

3.3 ✓Flow Speed – SLOW (rocker switch middle position)

3.4 ✓Speed CTRL – 5

3.5 sw Flow Direction → FORWARD (rocker switch bottom position)

Figure 4. CV Adjustment Rings

3.6 ✓**POIC** for adjustments to CV-A, CV-C, and/or Pump (Figure 4)

Observe and report bubble management of Diverter, Separator, and Water Trap.

3.7 **On POIC GO**

Open CV-C as directed.

Add/remove liquid using Syringe 1 as directed.

Adjust Speed CTRL as directed.

3.8 ✓**POIC** for Plant Water Management 30ml Syringe use

Open 30ml Syringe Stopcock (handle parallel to tubing).

Using 30ml Syringe, slowly depress plunger.

3.9 ✓**POIC** to report positions of CV-A and CV-C (Figure 4)

3.10 sw Flow Direction → OFF (rocker switch middle position)

3.11 Remove pump tubing from pump head. Refer to Pump Tubing (00:16).

OBJECTIVE:

To spot check the Plant Water Management Test Cell through ebb and flow.

NOTE

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3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA 1. EBB AND FLOW FROM TEST CELL BASE

1.1 ✓VOX configured for sound for hands-free communication

1.2 ✓Plant Water Management 120ml Syringe (two) tick marks are in FOV

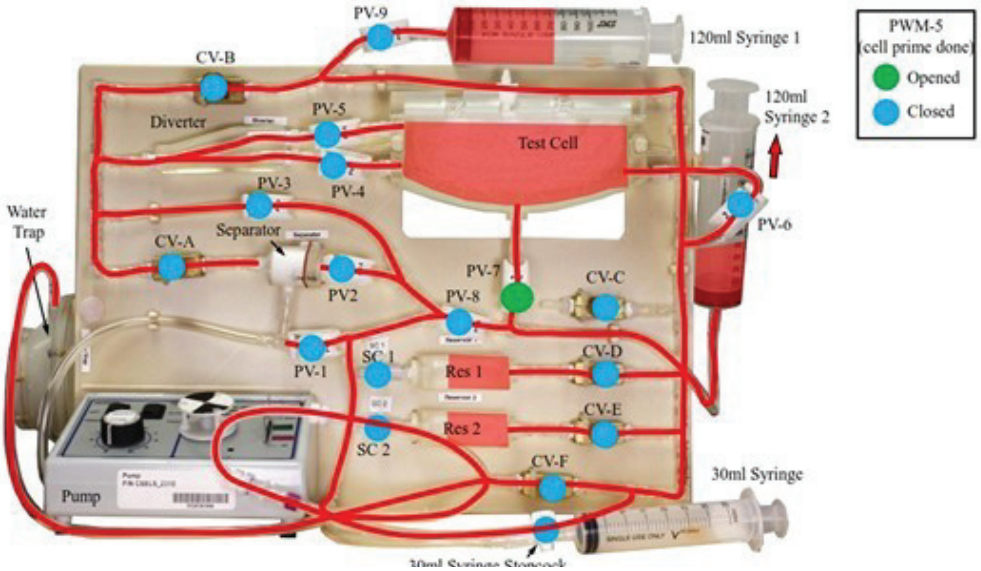

Figure 1. Ebb and Flow from Test Cell Base

1.3 **On POIC GO**

Open PV-7 (Figure 1).

✓All other valves are closed

1.4 Using Syringe 2, slowly withdraw as much liquid as possible from Test Cell without ingesting bubbles.

1.5 ✓**POIC** to add liquid to Test Cell as instructed

1.6 Repeat step 1.4 and step 1.5 three more times.

1.7 Close PV-7.

2. EBB AND FLOW FROM TEST CELL INLET AND OUTLET

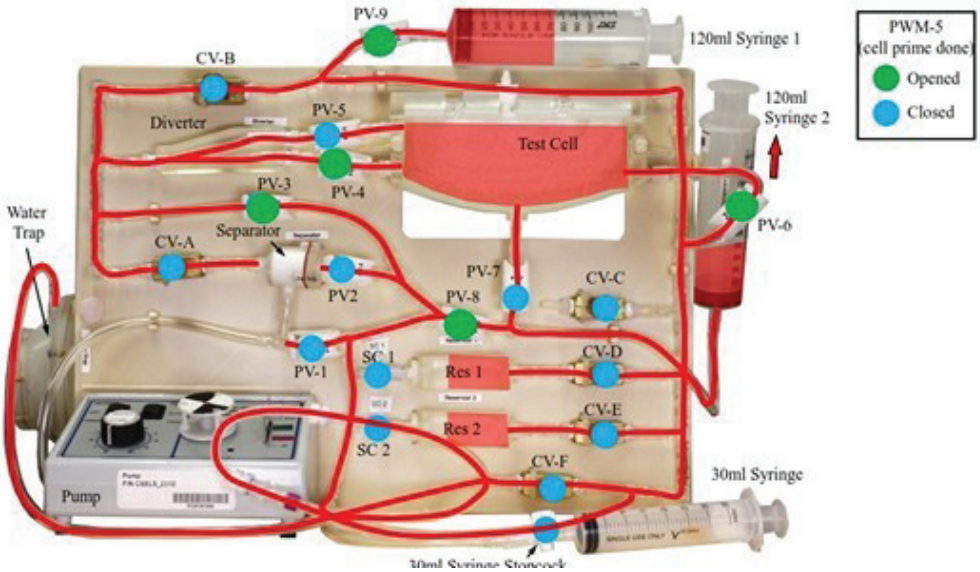

Figure 2. Ebb and Flow from Test Cell Inlet and Outlet

2.1 Open PV-8, PV-3, PV-4, PV-6, and PV-9 (Figure 2).

2.2 Using Syringe 2, slowly withdraw as much liquid as possible from Test Cell inlet without ingesting bubbles.

2.3 ✓**POIC** to add liquid to Test Cell as instructed

2.4 Repeat step 2.2 to step 2.3.

2.5 Using Syringe 1, slowly withdraw as much liquid as possible from Test Cell outlet without ingesting bubbles.

2.6 ✓**POIC** to add liquid to Test Cell as instructed

2.7 Repeat step 2.5 to step 2.6.

2.8 Using Syringe 1 and Syringe 2, slowly drain liquid from the Test Cell to the halfway point. Drain evenly into both syringes.

Parameters 1. Root Replacement

Root Test	Root Remove	Root Replace
[generic]	[remove]	[replace]
Root Test 1	Plant Water Management Root Type 4	Plant Water Management Root Type 1
Root Test 2	Plant Water Management Root Type 1 (three)	Plant Water Management Root Type 2
Root Test 3	Plant Water Management Root Type 2 (three)	Plant Water Management Root Type 3

OBJECTIVE:

To test root models for root zone, flow resistance, phase distributions, and stability.

PARTS:

Plant Water Management Root Kit P/N PWM5617:

Plant Water Management Root Type 1 P/N PWM5617-01 (three)
Plant Water Management Root Type 2 P/N PWM5617-02 (three)
Plant Water Management Root Type 3 P/N PWM5617-03 (three)

MATERIALS:

Dry Wipes (as needed)
Ziplock Bag

NOTE

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2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA 1. TEST CELL DRAIN AND ROOT REMOVAL

1.1 ✓VOX configured for sound for hands-free communication

1.2 ✓Plant Water Management 120ml Syringe (two) tick marks are in FOV

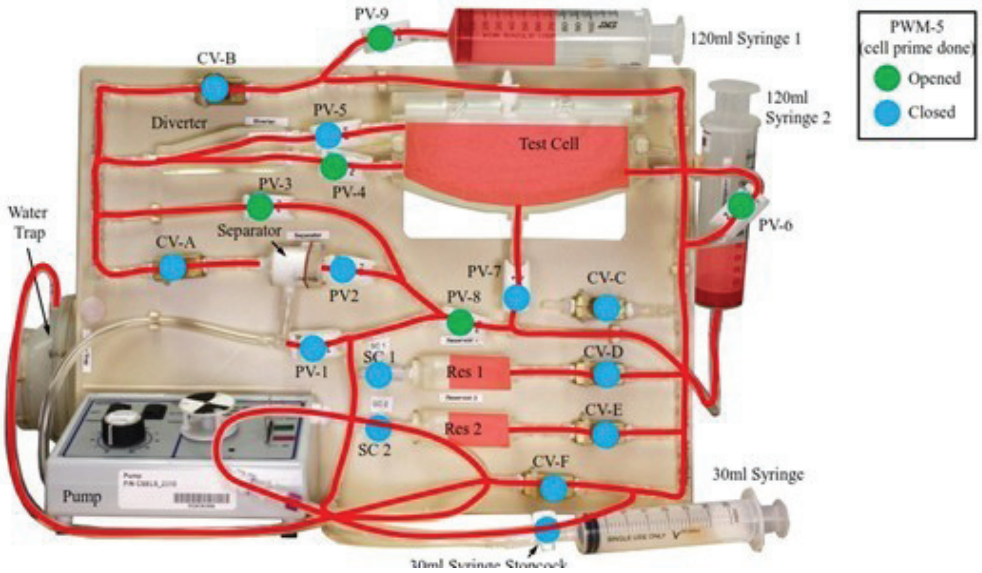

Figure 1. Prep for Test Cell Drain

1.3 Open PV-3, PV-4, PV-6, PV-8, and PV-9 (Figure 1).

1.4 ✓All other valves are closed

1.5 ✓**POIC** to report Plant Water Management 120ml Syringe (two) volumes

1.6 Using Syringe 1 and Syringe 2, slowly withdraw as much liquid as possible from the Test Cell without ingesting bubbles.

1.7 ✓**POIC** to report Test Cell volume

If further draining needed,

> Close PV-8, PV-3, PV-4, PV-6, and PV-9.
>
> Open PV-7.
>
> Using Syringe 2, slowly withdraw as much liquid as possible from the base of the Test Cell without ingesting bubbles.
>
> Close PV-7.

1.8 Open Test Cell lid by pulling tab. Refer to Root Remove (00:20).

Gently remove **[remove]** from Test Cell and place in Ziplock Bag [Dry Wipes].

1.9 Discard Ziplock Bag containing Dry Wipes and **[remove]**.

2. ROOT TYPE TEST

2.1 Insert stem of **[replace]** into one of the slots on Test Cell lid. Refer to Root Replace (00:53).

Gently guide roots inside and center beneath the stem.

2.2 Repeat step 2.1 for remaining **[replace]** (two).

2.3 **On POIC GO**

Open PV-7.

2.4 Using Syringe 2, slowly depress plunger to refill Test Cell with as much liquid as possible to just below pinning edge without introducing bubbles.

2.5 Using Syringe 2, slowly withdraw as much liquid from Test Cell as possible without ingesting bubbles.

2.6 Repeat step 2.4 and step 2.5 four more times.

2.7 Using Syringe 2, slowly depress plunger to refill Test Cell with as much liquid as possible to just below pinning edge without introducing bubbles.

2.8 Close PV-7.

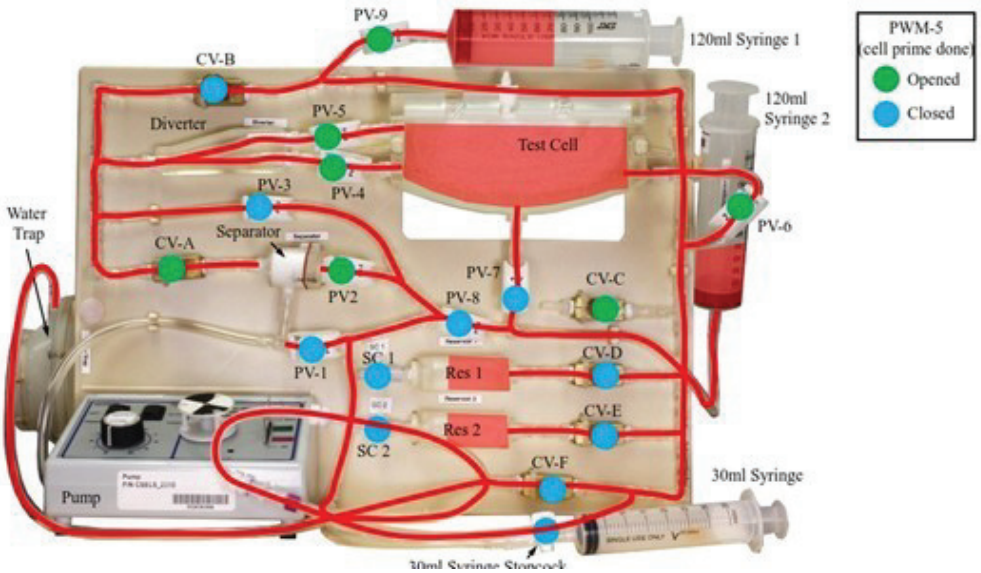

Figure 2. Root Type Test

2.9 ✓**POIC** for specified combination of aeration, separator, and water trap

Open PV-2, CV-A, PV-4, PV-5, PV-6, PV-9, and CV-C (Figure 2)

✓All other valves are closed

2.10 sw 120 VDC to 120 VAC Inverter SW2 → ON

2.11 Attach pump head tubing to pump head. Refer to Pump Tubing (00:16).

2.12 sw Flow Speed → SLOW (rocker switch middle position)

2.13 Turn Speed CTRL knob to 5.

2.14 sw Flow Direction → FORWARD (rocker switch bottom position)

Figure 3. CV Adjustment Rings

2.15 ✓**POIC** for CV-C adjustments (Figure 3)

2.16 sw Flow Direction → OFF (rocker switch middle position)

2.17 Close all valves.

2.18 Remove pump head tubing from pump head. Refer to Pump Tubing (00:16).

Ground should update IMS for the following parts:

Plant Water Management Root Type 1 P/N PWM5617-01 (three) TO: Temp stow in Ziplock Bag (step 1.9)

Plant Water Management Root Type 2 P/N PWM5617-02 (three) TO: Temp stow in Ziplock Bag (step 1.9)

Plant Water Management Root Type 3 P/N PWM5617-03 (three) TO: installed (step 2.1)

Plant Water Management Root Type 4 P/N PWM5617-04 (one) TO: Temp stowed in Ziplock Bag (step 1.9)

OBJECTIVE:

To test performance limits of the Separator and Water Trap.

MATERIALS:

Dry Wipe (if needed)
Ziplock Bag (if needed)

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA 1. SEPARATOR LIMITS

1.1 ✓VOX configured for sound for hands-free communication

1.2 ✓Plant Water Management 120ml Syringe (two) tick marks are in FOV

Figure 1. CV Adjustment Rings

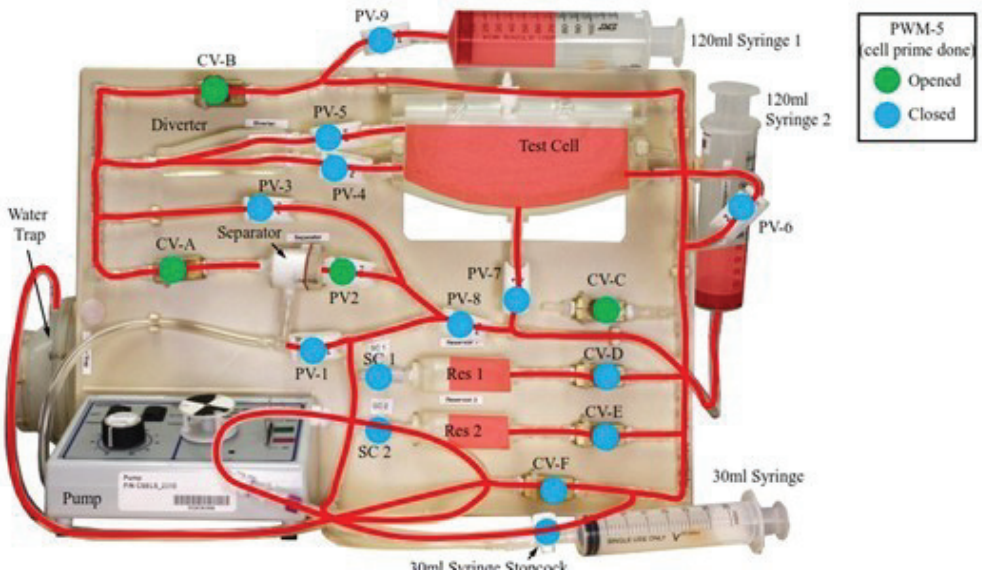

Figure 2. Separator Limits

1.3 ✓**POIC** for CV setpoints

Open CV-A and CV-C (Figure 1).

1.4 Open PV-2 and CV-B to full stop (Figure 2).

1.5 ✓All other valves are closed

1.6 Attach pump head tubing to pump head. Refer to Pump Tubing (00:16).

1.7 sw Flow Speed → SLOW (rocker switch middle position)

1.8 Turn Speed CTRL knob to 5.

1.9 sw Flow Direction → FORWARD (rocker switch bottom position)

1.10 ✓**POIC** to establish steady states

1.11 If significant water, about 10ml, enters Water Trap,

sw Flow Direction → OFF (rocker switch middle position)

1.12 sw Flow Direction → OFF (rocker switch middle position)

2. SEPARATOR LIMITS WITH TEST CELL FLOW

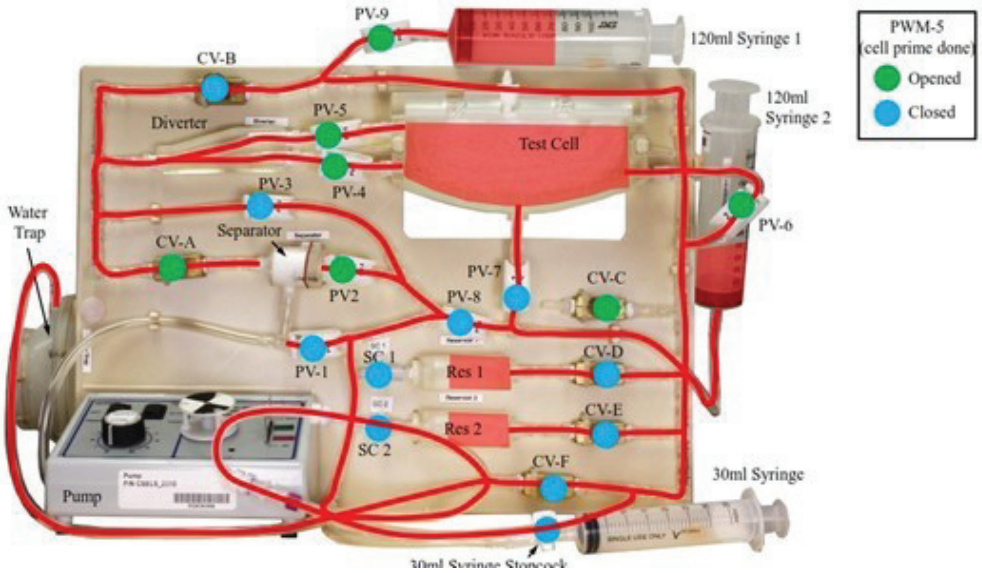

Figure 3. Separator Limits With Test Cell Flow

2.1 Close CV-B. (Figure 3)

2.2 Open PV-4, PV-5, PV-6, and PV-9. (Figure 3)

2.3 ✓PV-2, CV-A, and CV-C open

2.4 ✓All other valves are closed

2.5 sw Flow Direction → FORWARD (rocker switch bottom position)

2.6 ✓**POIC** to establish steady states

2.7 sw Flow Direction → OFF (rocker switch middle position)

3. WATER TRAP LIMITS

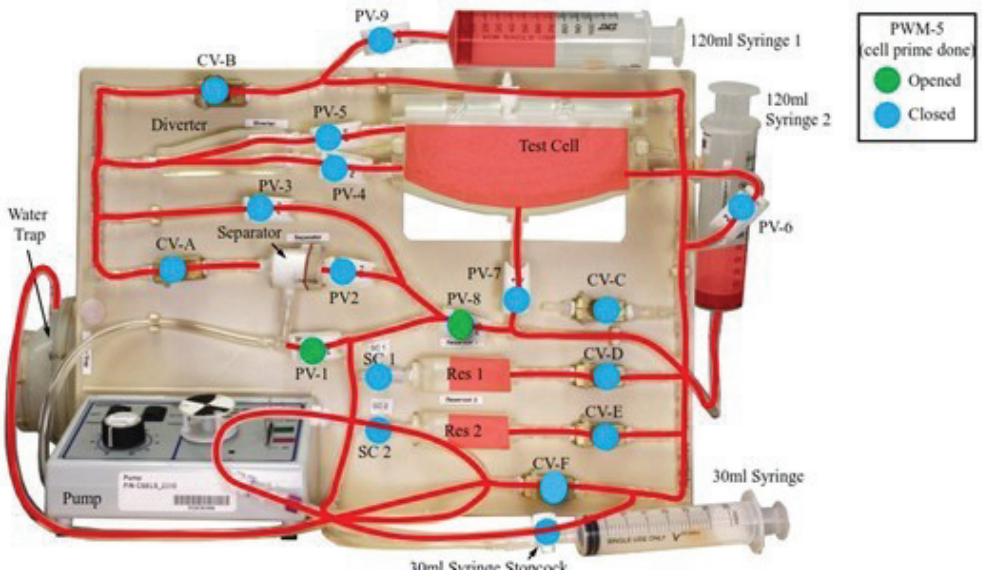

Figure 4. Water Trap Limits from Inlet

3.1 Open PV-1 and PV-8 (Figure 4).

3.2 ✓All other valves are closed

3.3 Using Syringe 2, slowly depress plunger to add 5ml of liquid to Water Trap inlet.

3.4 Close PV-1 and PV-8.

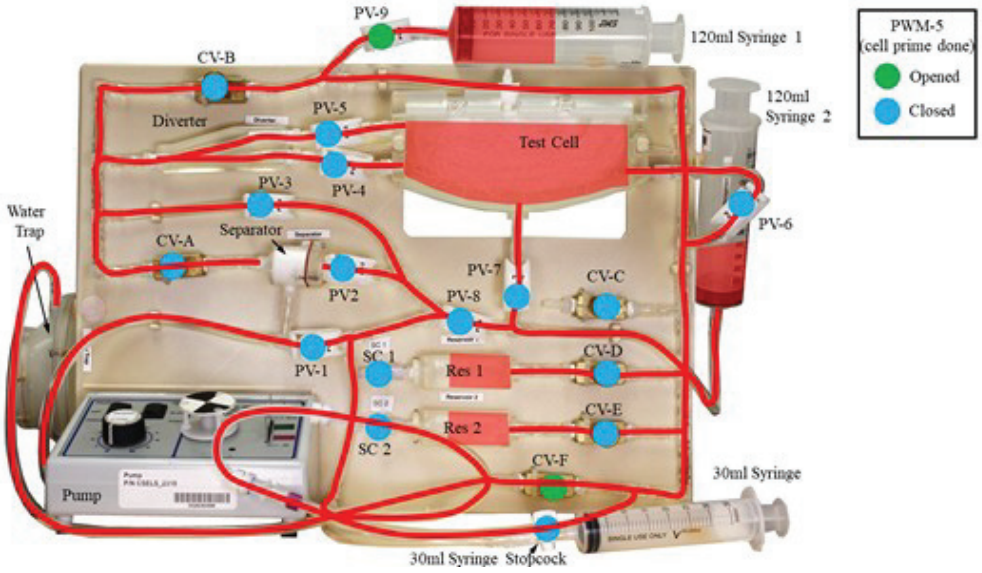

Figure 5. Water Trap Limits from Outlet

3.5 Open PV-9 and CV-F to full stop (Figure 5).

3.6 Using Syringe 1, slowly depress plunger to add 5ml of liquid to Water Trap outlet.

3.7 Close PV-9.

3.8 Open PV-1.

✓CV-F open

3.9 ✓All other valves are closed

3.10 sw Flow Direction → FORWARD (rocker switch bottom position)

3.11 ✓**POIC** to establish steady states

3.12 If significant water, about 10ml, enters Water Trap, or if droplets appear on outside of Water Trap,

sw Flow Direction → OFF (rocker switch middle position)

Gently remove any liquid on the outside of the Water Trap using Dry Wipe.

Place used Dry Wipe in Ziplock Bag. Discard.

3.13 Open Plant Water Management 30ml Syringe Stopcock and withdraw Plant Water Management 30ml Syringe plunger to fill with air.

Close 30ml Syringe Stopcock.

3.14 Using 30ml Syringe, slowly introduce small and large, single and multiple bubbles into the system.

3.15 ✓**POIC** to report Water Trap performance

If instructed

Repeat step 3.13 and step 3.14.

3.16 sw Flow Direction → OFF (rocker switch middle position)

3.17 Open PV-8.

3.18 Close CV-F.

3.19 ✓PV-1 open

3.20 Using Syringe 2, add 5ml of liquid.

3.21 Close PV-8.

3.22 Open CV-F.

3.23 ✓**POIC** for further instruction

If instructed,

Repeat step 3.9 to step 3.21.

3.24 Remove pump head tubing from pump head. Refer to Pump Tubing (00:16).

2.026 PLANT WATER MANAGEMENT 5 TEARDOWN AND STOW

OBJECTIVE:

To drain Plant Water Management 5, trash, and stow necessary hardware.

NOD2S4 1. TEST CELL DRAIN

NOTE
1. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
2. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
3. Vox Mode is required for hands-free communication.

1.1 ✓VOX configured for sound for hands-free communication

1.2 ✓Plant Water Management 120ml Syringe (two) tick marks are in FOV

1.3 ✓All valves are closed

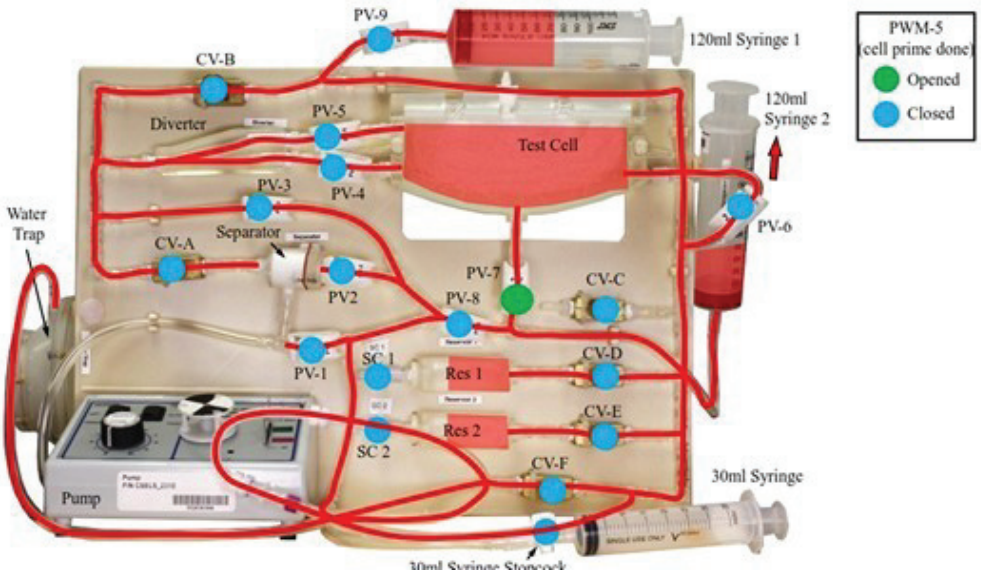

Figure 1. Drain Test Cell

1.4 Open PV-7 (Figure 1).

1.5 Using Syringe 2, rapidly remove 50ml of liquid from Test Cell (Figure 1).

1.6 Using Syringe 2, rapidly add 50ml of liquid back into Test Cell.

1.7 Repeat step 1.5 and step 1.6.

1.8 **On POIC GO**

Using Syringe 2, slowly remove all remaining liquid from Test Cell without ingesting bubbles.

1.9 Close PV-7.

1.10 Open Test Cell lid by pulling tab. Refer to Root Remove (00:20).

Gently remove Plant Water Management Root Type 3 (three) from Test Cell [Dry Wipe].

1.11 Place Plant Water Management Root Type 3 (three) and used Dry Wipes in Ziplock Bag. Temp stow.

1.12 Doff VOX.

2. PLANT WATER MANAGEMENT 5 TEARDOWN

2.1 sw 120 VDC to 120 VAC Inverter SW2 → OFF (S/N 1038)

2.2 Power Cable ←|→ Inverter GFCI Cable 3'

2.3 AWS Snowcone Power Supply →|← Inverter GFCI Cable 3'

2.4 Pump ←|→ Power Cable

2.5 ✓Pump head tubing is removed from pump head

2.6 Remove Pump.

Discard Gray Tape.

2.7 Temp stow Pump and Power Cable.

2.8 ✓All valves are closed

Figure 2. Plant Water Management 5 Mounting Points

2.9 Remove Plant Water Management 5 [#10 Fasteners] (Figure 2).

2.10 Discard Plant Water Management 5 and Ziplock Bag containing Plant Water Management Root Type 3 (three) and used Dry Wipes.

2.11 sw LED Work Light (two) → OFF

2.12 sw 120 VDC to 120 VAC Inverter SW3 → OFF (S/N 1038)

2.13 Work Light USB Power Cable (two) ←|→ Multi-Port USB Charger

2.14 Work Light USB Power Cable (two) ←|→ LED Work Light (two)

2.15 Remove LED Work Light (two) from Flexible Bracket (two).

2.16 Remove Flexible Bracket (two) from Seat Track.

2.17 Remove A-4 Printer Paper from Laptop Desk. Discard.

2.18 Remove Laptop Desk from Multi-Use Bracket.

2.19 Remove Multi-Use Bracket from Seat Track.

3. CAMCORDER RECONFIGURATION

3.1 AUDIO SETUP

NODE2 Cam 2

3.1.1 pb MENU → Press

3.1.2 Joystick → '  **Audio Select**'

3.1.3 Joystick → Press

3.1.4 Joystick → '**Select CH1/CH2 Input**'

3.1.5 Joystick → Press

3.1.6 Joystick → '**Input Terminals**'

3.1.7 Joystick → Press

3.1.8 pb MENU → Press

3.2 sw FULL AUTO → ON

3.3 sw FOCUS → A

3.4 sw IRIS → A

NODE2 Cam 1 & NODE2 Cam 2

3.5 sw POWER (two) → OFF

4. DATA DOWNLINK

4.1 Using Imagery Transfer Tool, transfer videos to Videos for Downlink, select 'For POIC', include card S/N (B/C) and input Plant Water Management into 'Input Brief Folder Description'.

4.2 Notify POIC S/N or B/C 256GB SD Card (two) used, retain until downlink confirmed on the ground.

5. Return deployed Photo/TV equipment.

6. Stow equipment per Stowage Note.

Ground should update IMS for the following parts:
Plant Water Management 5 P/N PWM5601-01 TO: trashed (step 2.10)
Pump P/N CSELS_2310 TO: stow (step 6)
Power Cable P/N CSELS_2310 TO: stow (step 6)
Multi-Use Bracket TO: stow (step 6)
Inverter GFCI Cable 3' TO: stow (step 6)
Laptop Desk TO: stow (step 6)
LED Work Light (two) TO: stow (step 6)
Plant Water Management Root Type 3 TO: trash (step 2.10)
Flexible Bracket (two) TO: stow (step 6)
Work Light USB Power Cable P/N WORKLIGHTCABLE (two) TO: stow (step 6)

2.027 PLANT WATER MANAGEMENT 6 MWA PREP AND HARDWARE SET UP

(PB3-01-2890 / IMPACT S) Page 1 of 8 pages

OBJECTIVE:

To set up Node 2 deployed camcorders, install Plant Water Management 6, and prep experiment for operations.

TOOLS:

MWA Utility Kit P/N SJG33110310-301:

#10 Fasteners (two)

Camcorder (two)

Multi-Use Bracket (two)

LED Work Light P/N WORKLIGHT-001 (two)

Inverter GFCI Cable 3' P/N SEG33123662-301

Laptop Desk

Bungee

Flexible Bracket (two)

Work Light USB Power Cable P/N WORKLIGHTCABLE-001 (two)

PARTS:

Plant Water Management 6 P/N PWM5601-02

Pump P/N CSELS_2310

Power Cable P/N CSELS_2320

MATERIALS:

A-4 Printer Paper

Gray Tape

Dry Wipe (as needed)

Cable Tie

Lens Cloth

Kapton Tape

Ziplock Bag

1. HARDWARE MWA INSTALLATION

NODE2 Cam 1

1.1 Set up NODE2 Camcorder for live over-the-shoulder video with FOV of MWA area.

1.2 ✓**POIC** for FOV

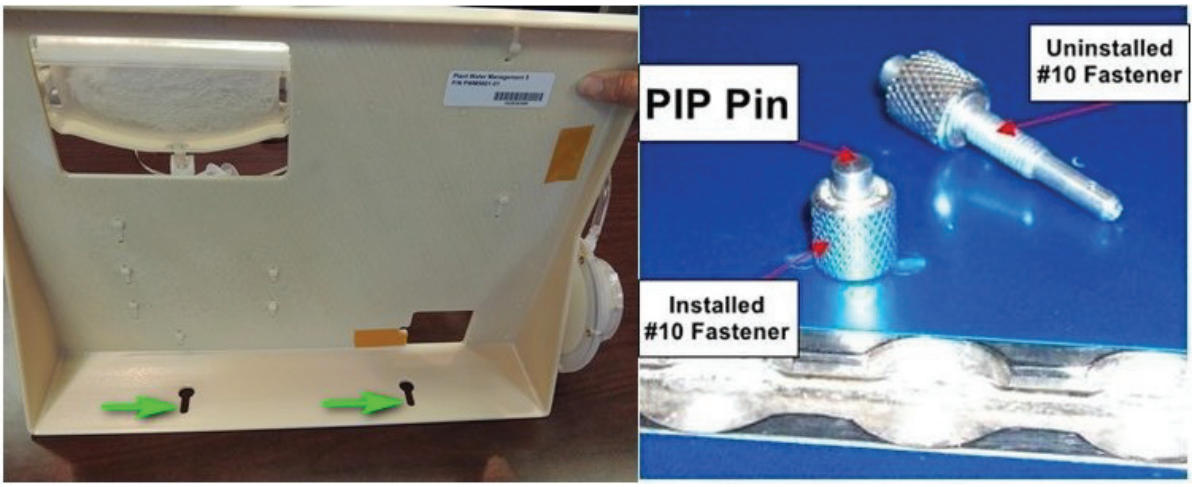

Figure 1. Mounting Points and #10 Fasteners

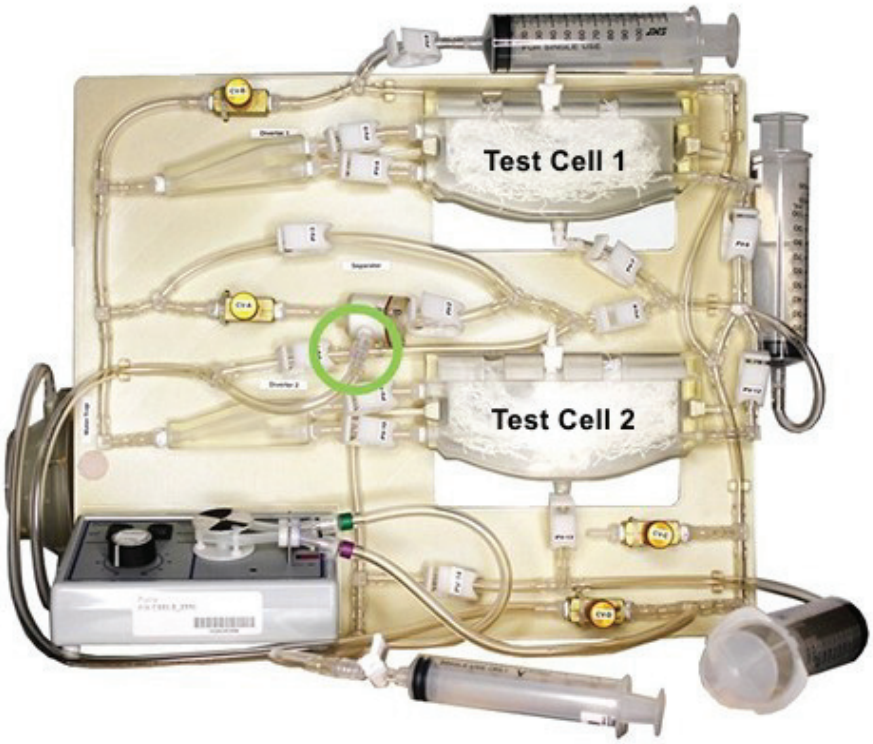

Figure 2. Luer Lock Attachment

NOD2S4

1.3 Use keyhole locations to install Plant Water Management 6 on MWA, leaving approximately 6 to 10 inches space between back of the test stand and the Crew Quarters [#10 Fasteners (two)] (Figure 1).

1.4 Attach luer lock to Separator by pushing and turning CW one quarter turn (Figure 2).

1.5 For Test Cell 1, open lid by gently pulling tab (Figure 2).

1.6 Evenly disperse roots throughout Test Cell volume.

1.7 Insert root stem into center slot on Test Cell lid.

1.8 Close Test Cell lid. Secure tab.

1.9 Repeat step 1.5 through step 1.8 for Test Cell 2.

1.10 ✓All tubing is connected

```
**********************************************************************************
*
*
*   If any damage to hardware,
*
*
*   |   ✓POIC
*
**********************************************************************************
```

2. PUMP INSTALLATION

Figure 3. Pump in the OFF State

Pump 2.1 ✓sw Flow Direction – OFF (rocker switch middle position, Figure 3)

Turn Speed CTRL knob to 0.

2.2 Attach Pump to MWA [Gray Tape] (Figure 2).

NOD2S4 2.3 ✓120 VDC to 120 VAC Inverter SW2 – OFF (S/N 1038)

2.4 Route Power Cable through back of Plant Water Management 6.

Pump →|← Power Cable

2.5 AWS Snowcone Power Supply ←|→ Inverter GFCI Cable 3'

2.6 Coil AWS Snowcone Power Supply. Temp stow.

2.7 Power Cable →|← Inverter GFCI Cable 3’

2.8 ✓Inverter GFCI Cable 3' →|← 120 VDC to 120 VAC Inverter J2 (S/N 1038)

2.9 sw 120 VDC to 120 VAC Inverter SW2 → ON (S/N 1038)

Inverter GFCI Cable 3'

2.9.1 pb RESET → Press (Green LED)

pb TEST → Press

Verify RESET pops out

If RESET does not pop out or LED not illuminated,

- sw 120 VDC to 120 VAC Inverter SW2 → OFF (S/N 1038)
- Repeat step 2.9 and step 2.9.1
- If second attempt fails,
  - Replace Inverter GFCI Cable 3'
  - Report S/N or B/C to **POIC**

pb RESET → Press (Green LED)

3. PUMP FUNCTIONAL TEST

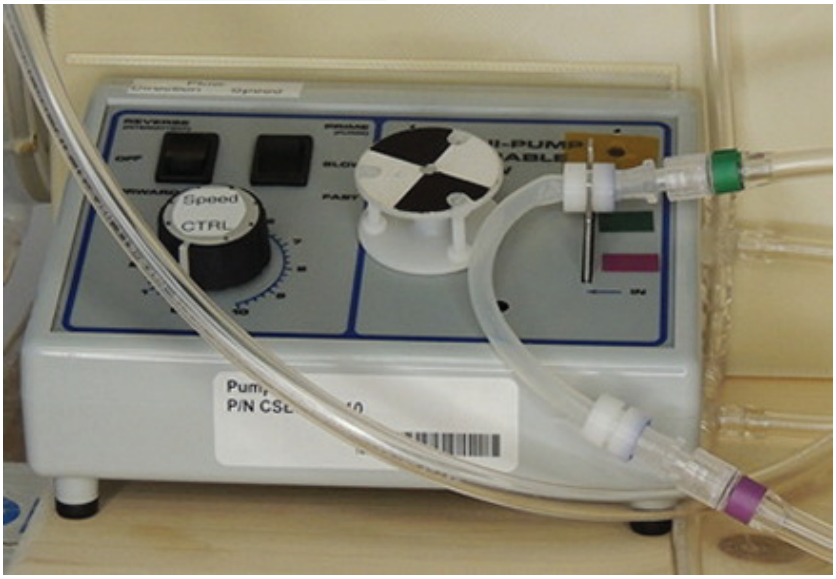

Figure 4. Pump Tubing Disconnected

3.1 ✓Pump head tubing removed from pump head (Figure 4)

3.2 sw Flow Speed → SLOW (rocker switch middle position)

3.3 Turn Speed CTRL knob to 8.

3.4 sw Flow Direction → FORWARD (rocker switch bottom position)

3.5 While pump is on, turn Speed CTRL knob CW to increase speed. Verify pump speed increases.

3.6 sw Flow Direction → OFF (rocker switch middle position)

3.7 Turn Speed CTRL knob to 0.

4. LIGHTING AND CAMCORDER SETUP

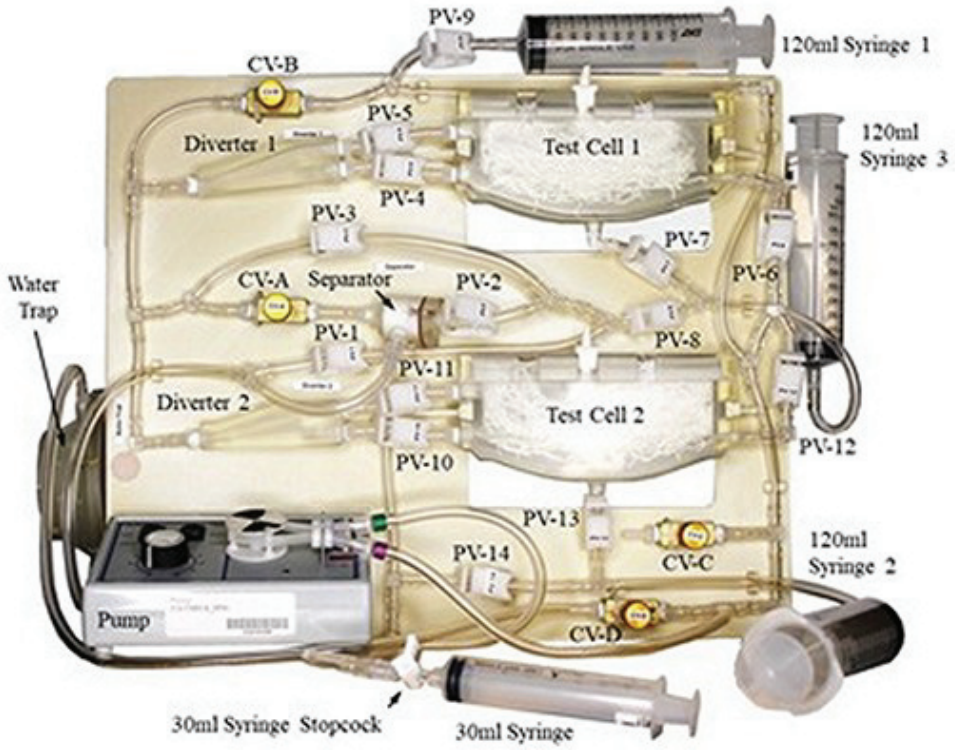

Figure 5. Hardware Configuration

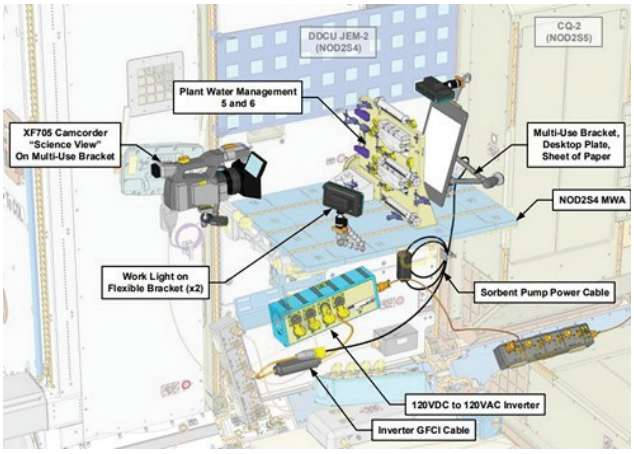

Figure 6. MWA Setup

4.1 ✓Plant Water Management 6 matches Figure 5

4.2 Attach Multi-Use Bracket to Seat Track behind Plant Water Management 6 (Figure 6).

4.3 Attach Laptop Desk to Multi-Use Bracket behind Plant Water Management 6 (Figure 6).

4.4 Secure A-4 Printer Paper behind Plant Water Management 6 (portrait orientation) on Laptop Desk [Kapton Tape].

4.5 Attach Flexible Bracket to Seat Track behind Plant Water Management 6 (Figure 6).

4.6 Attach second Flexible Bracket to Seat Track in front of Plant Water Management 6 (Figure 6).

4.7 Mount LED Work Light (two) to Flexible Bracket (two).

4.8 ✓Multi-Port USB Charger →|← Inverter GFCI Cable 3'

4.9 If Multi-Port USB Charger not present,

- 4.9.1 ✓**MCC-H** for Multi-Port USB Charger and Inverter GFCI Cable 3' stowage location
- 4.9.2 ✓sw 120 VDC to 120 VAC Inverter SW3 – OFF (S/N 1038)
- 4.9.3 Multi-Port USB Charger →|← Inverter GFCI Cable 3'
- 4.9.4 Inverter GFCI Cable 3' →|← 120 VDC to 120 VAC Inverter J3
- 4.9.5 sw 120 VDC to 120 VAC Inverter SW3 → ON (S/N 1038)
- 4.9.6 pb RESET → Press (Green LED)

Inverter GFCI Cable 3'

pb TEST → Press

Verify RESET pops out

If RESET does not pop out or LED not illuminated,

sw 120 VDC to 120 VAC Inverter SW3 → OFF (S/N 1038)

Repeat step 2.9 and step 2.9.1

If second attempt fails,

Replace Inverter GFCI Cable 3'

Report S/N or B/C to **POIC**

pb RESET → Press (Green LED)

4.10 Work Light USB Power Cable (two) →|← LED Work Light (two)

4.11 Work Light USB Power Cable (two) →|← Multi-Port USB Charger

4.12 sw LED Work Light (two) → ON

NOTE

1. Camcorder to be mounted on a Multi-Use Bracket about 3 1/2 feet from the Crew Quarters. Camcorder should NOT be mounted directly to MWA. The Camcorder needs to provide an independent record of motion to avoid loss of science data.
2. The face of the lens of the Camcorder needs to be at least three feet (36 inches) from the front face of Plant Water Management 6 to ensure the ability to focus and reduce lensing effects such as fisheye.

4.13 Attach Multi-Use Bracket to Seat Track.

NODE2 Cam 2

4.14 Attach second NODE2 Camcorder to Multi-Use Bracket.

4.15 Set up second NODE2 Camcorder for live downlink with close-up view of MWA (Figure 6).

4.16 ✓**POIC** for FOV and LED Work Light adjustments

4.17 Clean Camcorder lens as needed for best video imagery [Lens Cloth].

5. OVERNIGHT SAFING

5.1 sw 120 VDC to 120 VAC Inverter SW2 → OFF (S/N 1038)

5.2 Secure the Inverter GFCI Cable 3' (two) to Inverter Switch Guard at SW2 and SW3 [Cable Tie] (if required, allow for a bend radius of approximately 1.5 in). Refer to 3.104 120 VDC TO 120 VAC INVERTER/GFCI OPERATIONAL CONSTRAINTS (US SODF: CSS: 3. Plug-In Plans: 3.1 Reference)

5.3 sw LED Work Light (two) → OFF

5.4 Place 2.0 CTB over hardware on MWA and secure with Bungee.

✓Plant Water Management 6 and Pump are covered

NODE2 Cam 1 & NODE2 Cam 2

5.5 sw POWER (two) → OFF

5.6 Stow per Stowage Note.

Ground should update IMS for the following parts:
Bungee TO: installed (step 5.4)
Plant Water Management 6 TO: installed (step 1.3)

Pump P/N CSELS_2310 TO: installed (step 2.2)
Power Cable P/N CSELS_2320 TO: installed (step 2.7)
Multi-Use Bracket TO: installed (step 4.2)
LED Work Light (two) TO: installed (step 4.7)
Inverter GFCI Cable 3' TO: installed (step 2.7)
Laptop Desk TO: installed (step 4.3)
Flexible Bracket (two) TO: installed (step 4.5)
Work Light USB Power Cable P/N WORKLIGHTCABLE-001 (two) TO: installed (step 4.11)

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
PWM5_6-UHR-01	Hazardous Materials	CZ1/5	Go to step 1.10
UNQ-CSELSKIT2-02	Electrical	CZ2/2	Go to step 2.3, step 2.7, step 2.8, and step 2.9.1
UNQ-CSELSKIT2-02	Electrical	CZ2/3	Go to step 2.3 and step 2.9.1
UNQ-CSELSKIT2-02	Electrical	CZ2/4	Go to step 5.2
OCAD 102431	Electrical	OCAD 102431	Go to step 2.7, step 2.8, step 2.9, step 2.9.1, step 4.8, step 4.9.3, step 4.9.4, step 4.9.5, step 4.9.6, and step 4.12
STD-PWM-01	Flammability	CTL-4/4.1	Go to step 5.6
STD-CSELS-KIT2-01	Flammability	CTL-2/2.2	Go to step 5.4
AX-SNOW-UHR-1	Electrical	1/2	Go to step 2.3
OCAD 102397	Electrical	OCAD 102397	Go to step 4.8, step 4.9.2, step 4.9.3, step 4.9.4, step 4.9.6, step 4.10and step 4.11
OCAD 102398	Electrical	OCAD 102398	Go to step 4.9.2and step 4.9.6
OCAD 123070	Electrical	OCAD 123070	Go to step 4.8 and step 4.9.4
OCAD 123240	Electrical	OCAD 123240	Go to step 5.4

2.028 PLANT WATER MANAGEMENT 6 FLUID PREP AND SYSTEM PRIMING

OBJECTIVE:

To prime Plant Water Management 6 in preparation for experimentation.

MATERIALS:

Dry Wipe (as needed)
Ziplock Bag
Beverage BOB:
Tropical Punch Drink Bag (two)
Beverage Straw Assembly

TOOLS:

Hands-free VOX

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

1. TEST FLUID TRANSFER TO TEST STAND KIT

PWD

1.1 Fill Tropical Punch Drink Bag (two) at PWD.

1.2 Shake Tropical Punch Drink Bag (two) vigorously.

Temp stow for five minutes for particles to dissolve.

MWA

1.3 ✓NODE 2 Camcorder with close-up view of MWA still recording to 256GB SD Card (two)

1.4 View Liquid Transfer video (01:09).

1.5 Temp stow Dry Wipes near MWA.

1.6 Demate Plant Water Management 120ml Syringe (Syringe 1) from tubing.

1.7 Mate Beverage Straw Assembly to Syringe 1 [Dry Wipe].

1.8 Mate Tropical Punch Drink Bag to Beverage Straw Assembly [Dry Wipe].

1.9 Open clamp on Beverage Straw Assembly and draw 120ml of fluid into Syringe 1.

Close clamp on Beverage Straw Assembly [Dry Wipe].

1.10 If air bubbles are drawn into syringe from the bag,

Demate Syringe 1 from Beverage Straw Assembly.

Use centrifugal force method to push air toward the tip of the syringe.

Dispense air into a Dry Wipe.

Repeat fill from bag and centrifuge method until syringe has at least 110ml of bubble-free fluid (bubbles less than 1mm in diameter are okay).

1.11 Demate Syringe 1 from Beverage Straw Assembly [Dry Wipe].

1.12 Mate Syringe 1 to tubing and then mount to Plant Water Management 6 with attached Velcro [Dry Wipe].

1.13 Repeat step 1.6 to step 1.12 for Syringe 2 and Syringe 3.

1.14 Temp stow Beverage Straw Assembly and Tropical Punch Drink Bag.

1.15 Place used Dry Wipes in Ziplock Bag. Discard.

2. TUBING PRIME

NOTE

1. Obstruction-free, close-up Camcorder view should be maintained during experiment.
2. When priming to TEE fitting, liquid should only be moved until flush with the junction so that the other legs of the TEE fitting are not occluded.

2.1 ✓VOX configured for sound for hands-free communication

2.2 ✓**POIC** to ensure proper configuration before priming

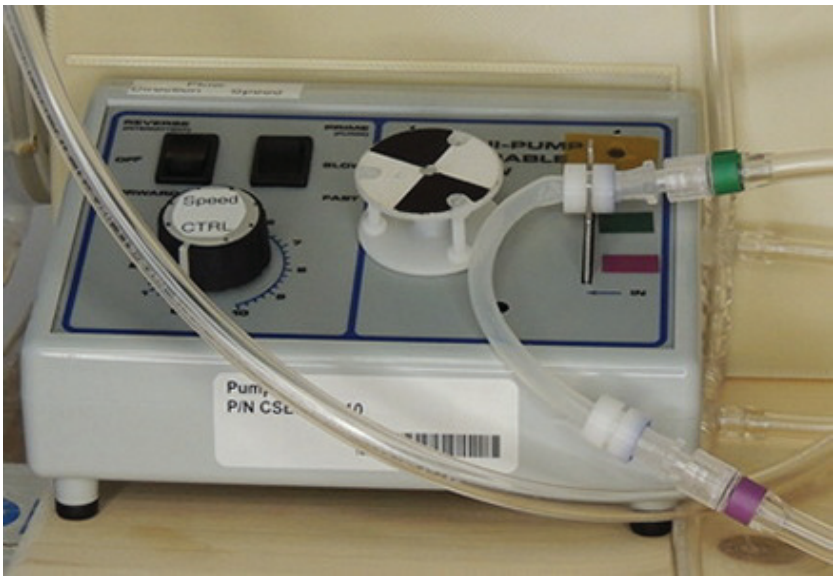

Figure 1. Pump Hose Unconnected

2.3 Ensure Pump Hose is disconnected from Pump Head (Figure 1).

2.4 ✓All valves are closed

2.5 Open PV-7.

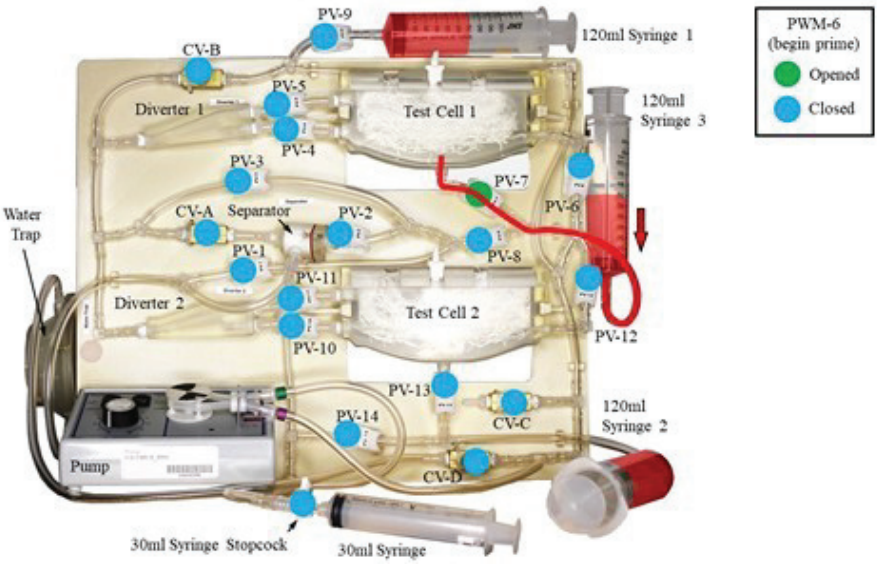

Figure 2. Prime to Bottom of Test Cell 1

2.6 Using Syringe 3, prime tubing through PV-7 until flush with bottom of Test Cell 1 (Figure 2).

2.7 Close PV-7.

2.8 Open PV-8 and PV-2.

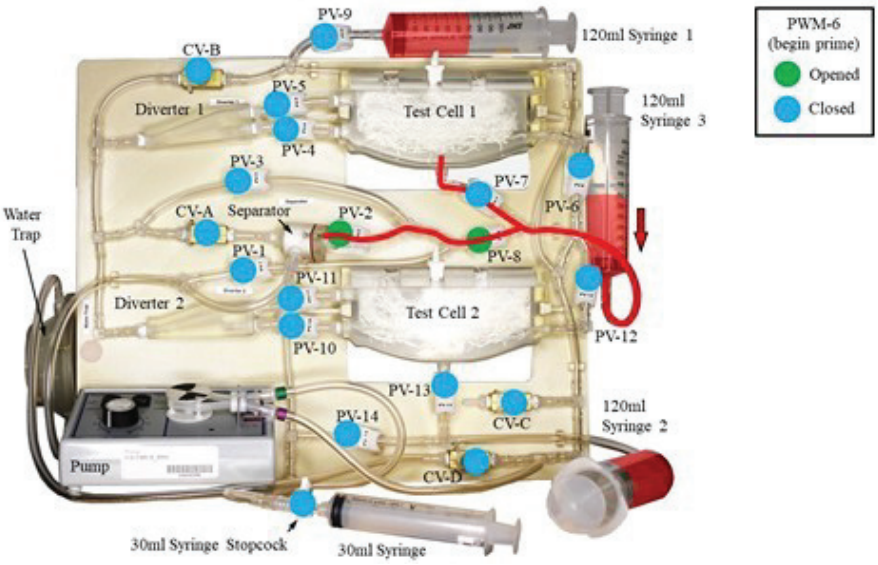

Figure 3. Prime to Entrance of Separator

2.9 Using the Syringe 3, prime tubing through PV-8, PV-2, and up to the entrance of the Separator (Figure 3).

2.10 Close PV-2.

2.11 Open PV-1.

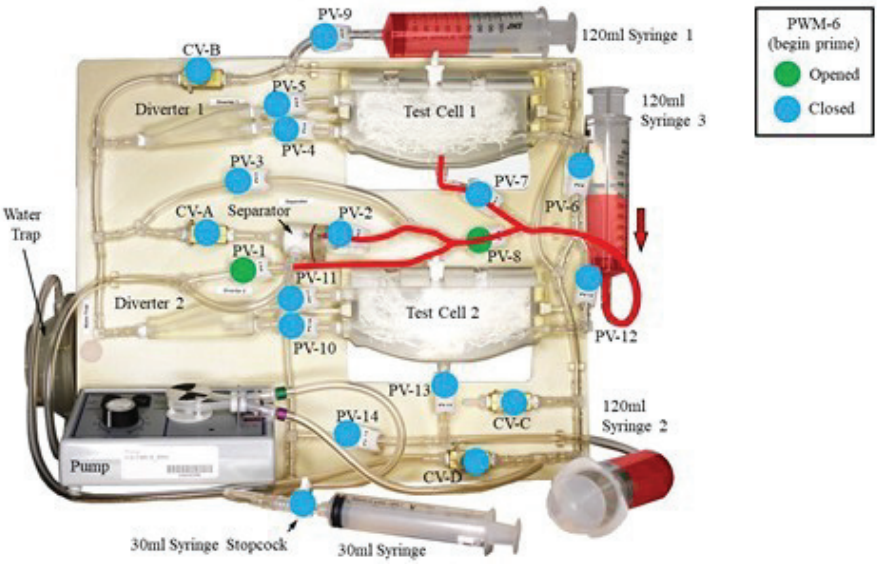

Figure 4. Prime to TEE fitting upstream of PV-1

2.12 Using the Syringe 3, prime tubing up to the TEE fitting upstream from PV -1 (Figure 4).

2.13 Close PV-1.

2.14 Open CV-A to full stop and PV-3.

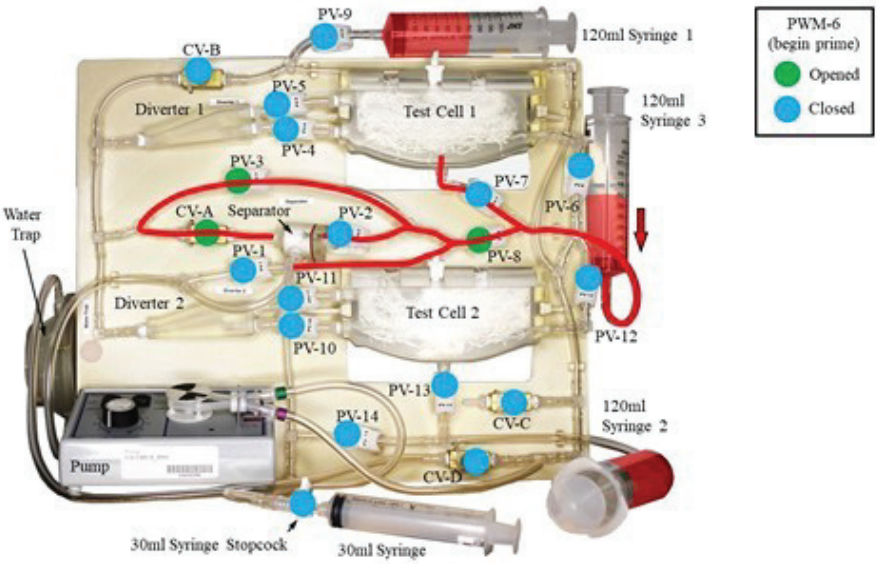

Figure 5. Prime to Exit of Separator

2.15 Using Syringe 3, prime tubing through CV-A and up to the Separator outlet (Figure 5).

2.16 Close CV-A.

2.17 Open PV-5.

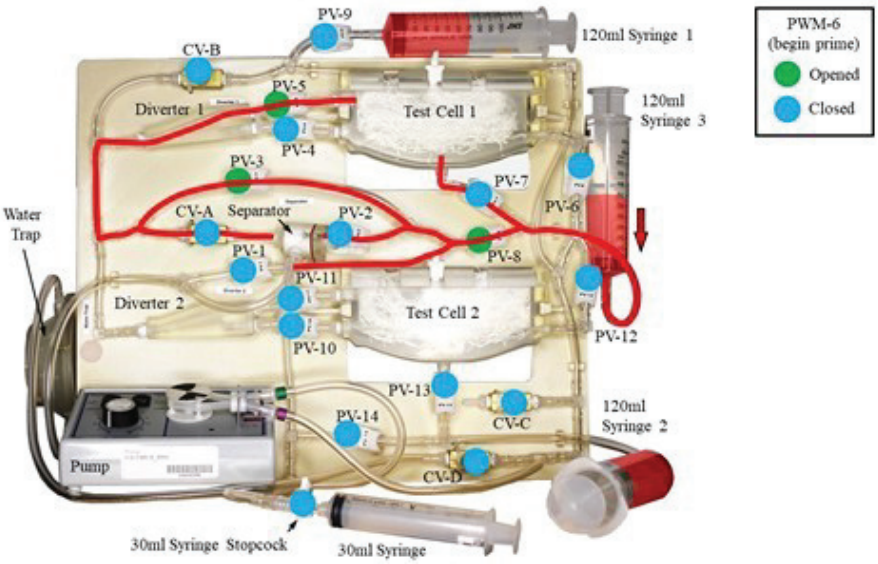

Figure 6. Prime through PV-5 to Test Cell

2.18 Using Syringe 3, prime tubing through PV-5 until flush with Test Cell 1 inlet (Figure 6).

2.19 Close PV-5.

2.20 Open PV-4.

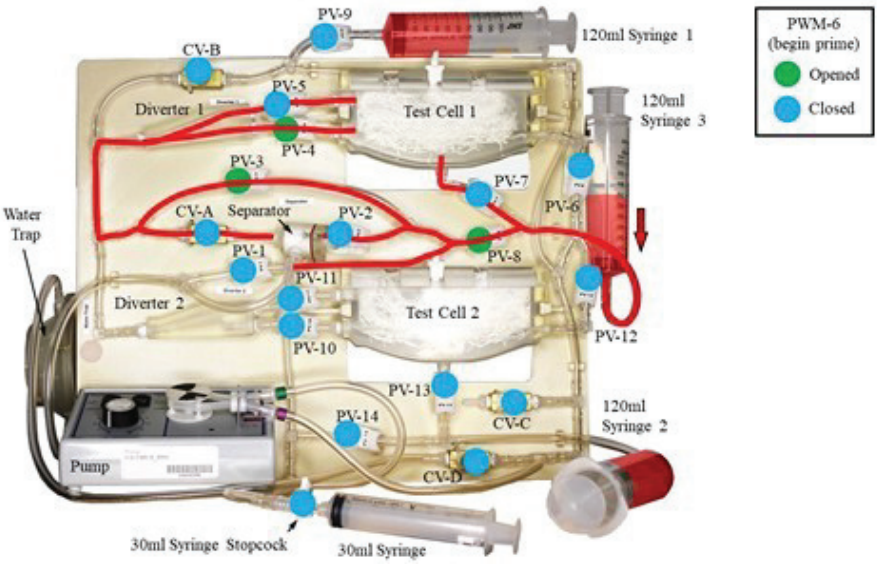

Figure 7. Prime through PV-4 to Test Cell

2.21 Using Syringe 3, prime tubing through PV-4 until flush with Test Cell 1 inlet (Figure 7).

2.22 Close PV-4.

2.23 Open CV-B to full stop and PV-6.

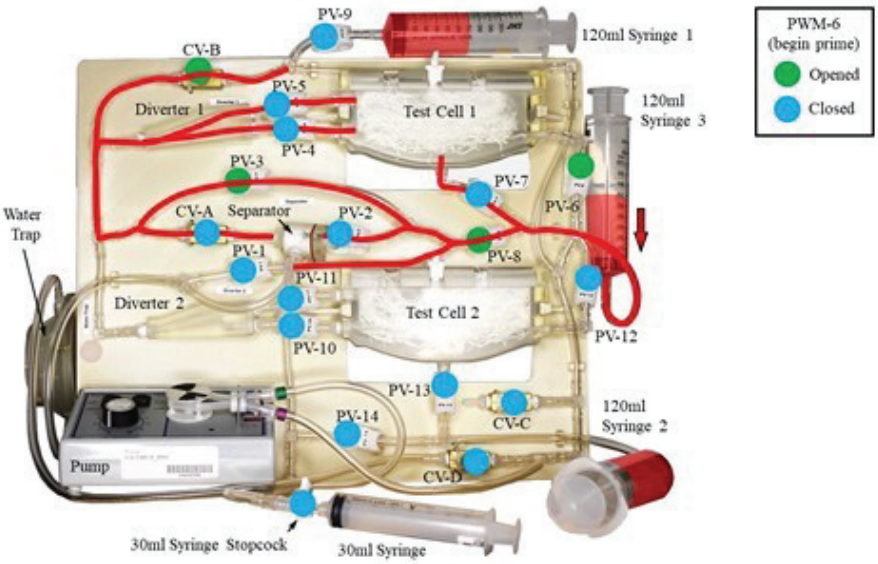

Figure 8. Prime to Y-fitting

2.24 Using Syringe 3, prime tubing through CV-B and up to the Y-fitting (Figure 8).

2.25 Close CV-B, PV-6, PV-3, and PV-8.

2.26 Open CV-D to full stop and PV-9.

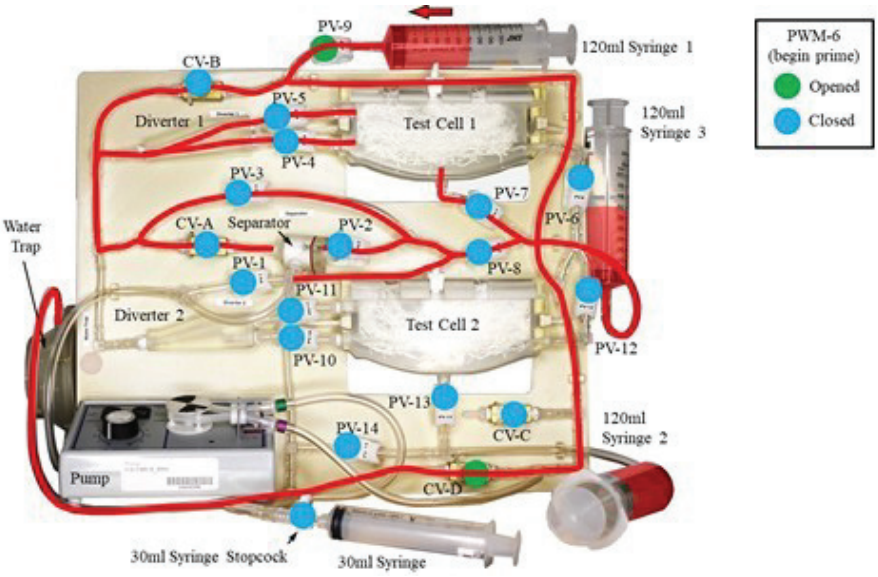

Figure 9. Prime to Water Trap

2.27 Using Syringe 1, prime tubing through CV-D until flush with Water Trap connector (Figure 9).

2.28 Open PV-14 and 30ml Syringe Stopcock (handle parallel to tubing).

Close CV-D.

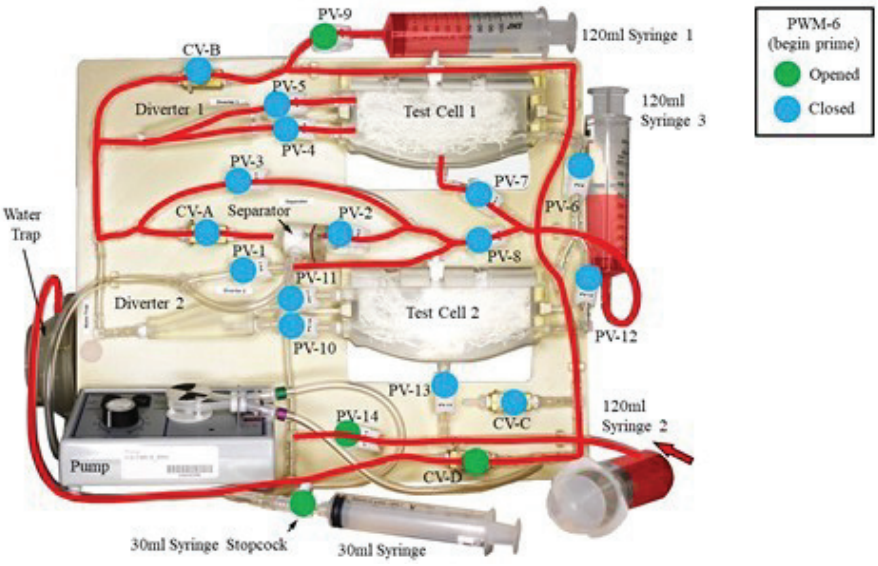

Figure 10. Prime through PV-14 to TEE fitting

2.29 Using Syringe 2, prime tubing through PV-14 and stop at TEE fitting (Figure 10).

2.30 Close PV-14 and 30ml Syringe Stopcock (handle perpendicular to tubing).

2.31 Open PV-13.

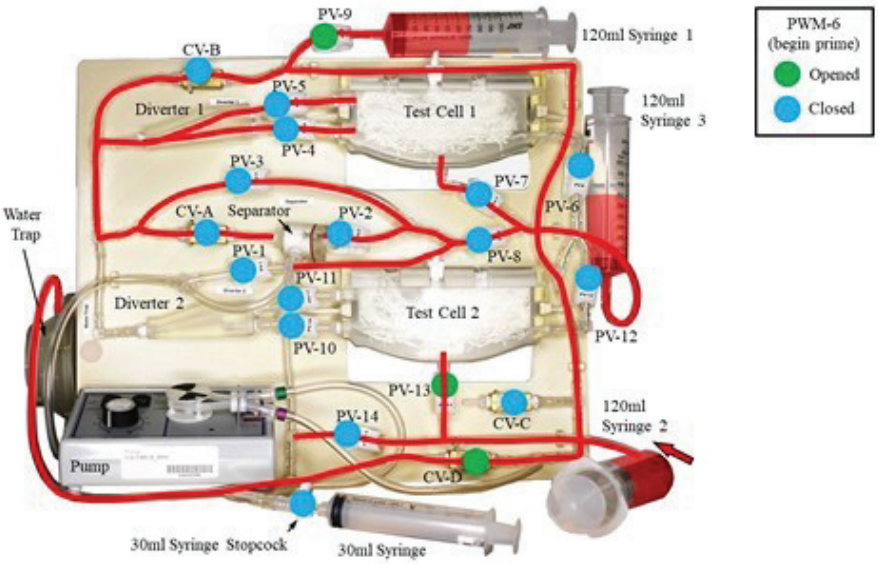

Figure 11. Prime to Bottom of Test Cell 2

2.32 Using Syringe 2, prime through PV-13 until flush with Test Cell 2 base (Figure 11).

2.33 Close PV-13.

2.34 Open PV-1.

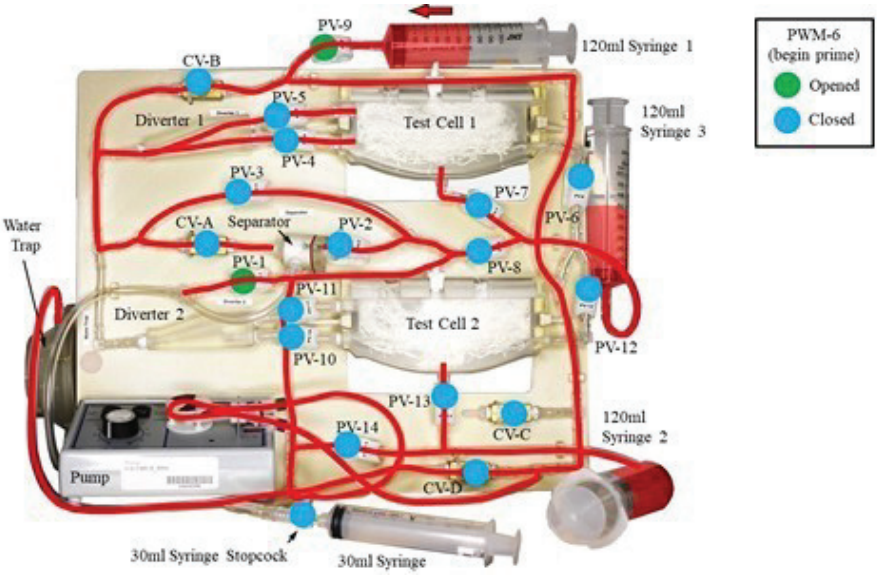

Figure 12. Prime to Y-fitting

2.35 Using Syringe 1, prime through pump head tubing, PV-1, and up to the Y -fitting (Figure 12).

2.36 Close PV-1.

2.37 Open PV-6.

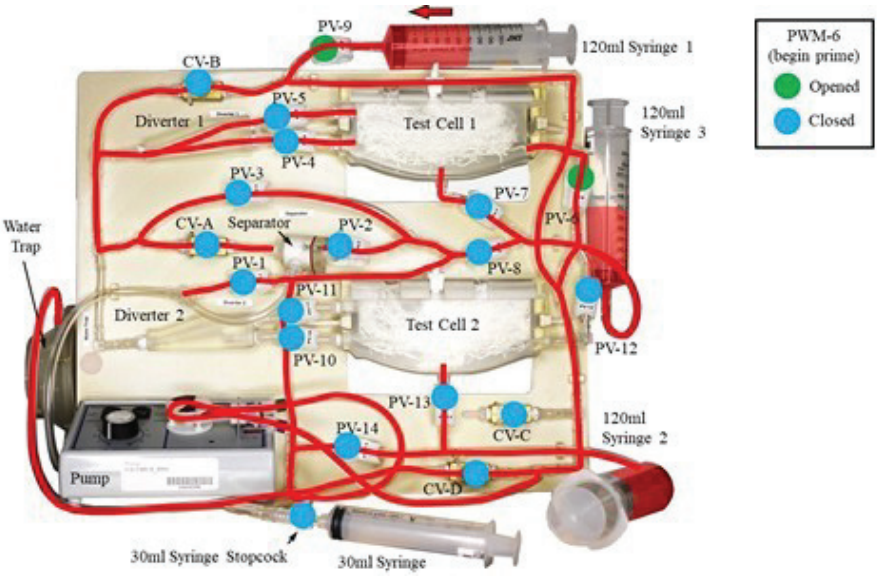

Figure 13. Prime to Test Cell 1 Outlet

2.38 Using Syringe 1, prime tubing through PV-6 until flush with Test Cell 1 Outlet (Figure 13).

2.39 Close PV-6.

2.40 Open CV-B to full stop and PV-11.

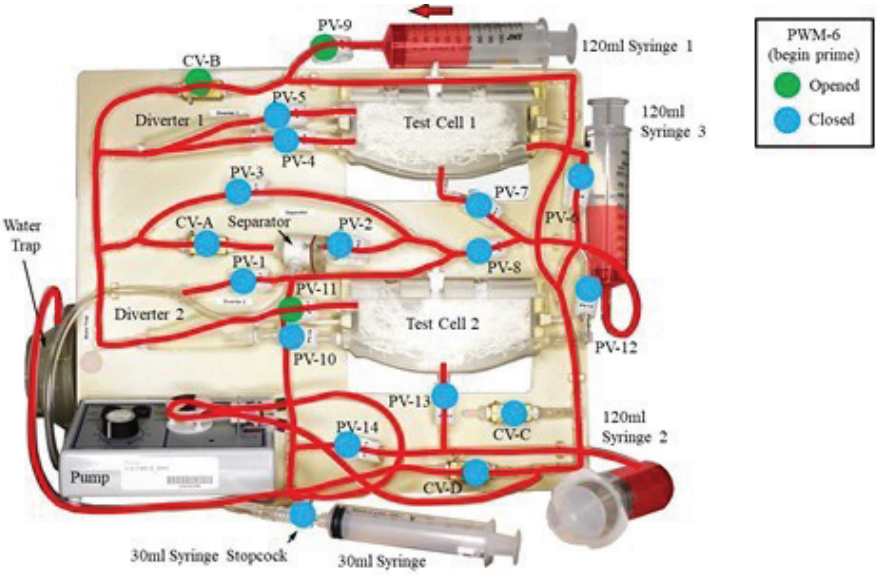

Figure 14. Prime through PV-11 to Test Cell Inlet

2.41 Using Syringe 1, prime through Diverter 2, PV-11, and flush with the inlet of Test Cell 2 (Figure 14).

2.42 Close PV-11.

2.43 Open PV-10.

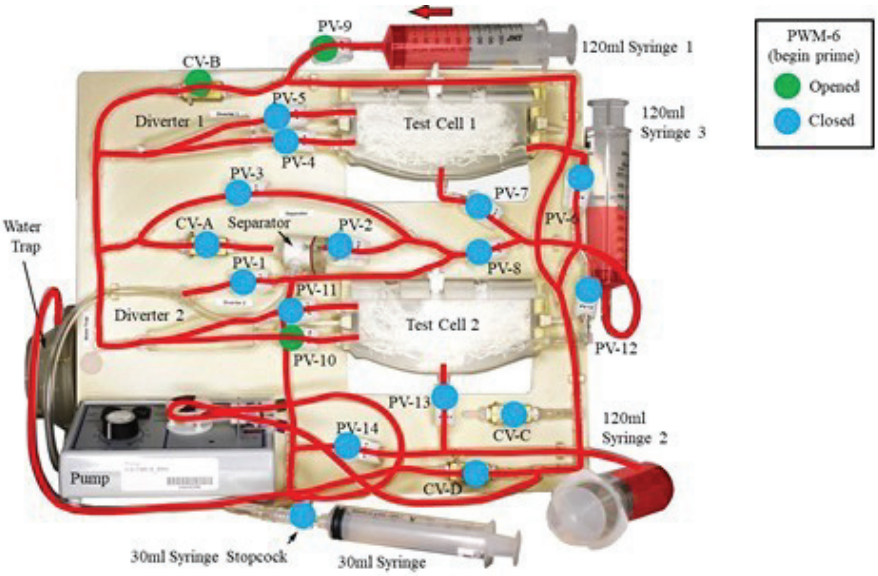

Figure 15. Prime through PV-10 to Test Cell Inlet

2.44 Using Syringe 1, prime through PV-10 and flush with the inlet of Test Cell 2 (Figure 15).

2.45 Close CV-B and PV-10.

2.46 Open PV-12.

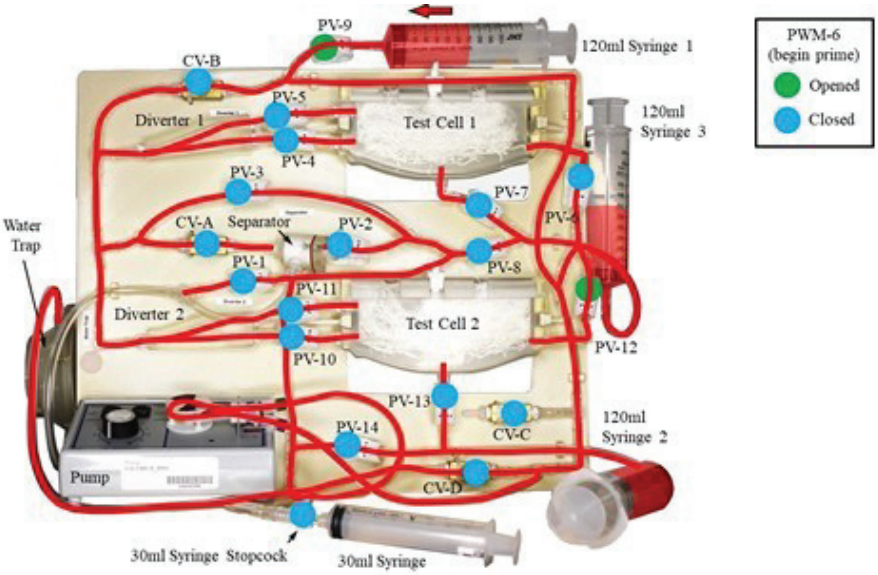

Figure 16. Prime to Test Cell Outlet

2.47 Using Syringe 1, prime through PV-12 and flush with Test Cell 2 outlet (Figure 16).

2.48 Close PV-12 and PV-9.

2.49 ✓**POIC** to confirm tube priming complete

3. TEST CELL 1 PRIME

3.1 Open PV-7.

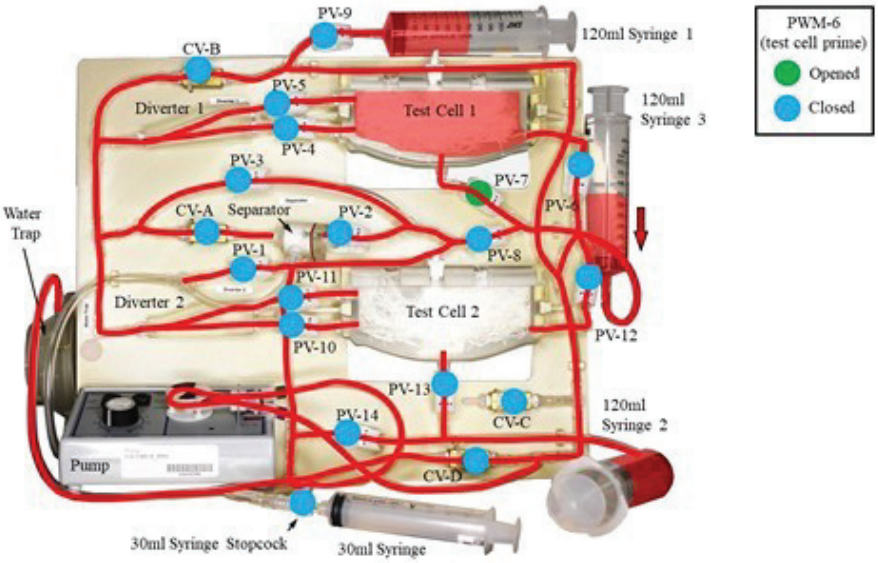

Figure 17. Prime Test Cell 1 through base

3.2 Using Syringe 3, slowly prime Test Cell 1, attempting to deliver the highest stable liquid volume possible with a single plunge, adjusting plunge rate as necessary (Figure 17).

3.3 Close PV-7.

3.4 ✓**POIC** to report Test Cell 1 fill level

If instructed,

3.4.1 Open PV-8, PV-9, PV-3, PV-4, and PV-6.

~

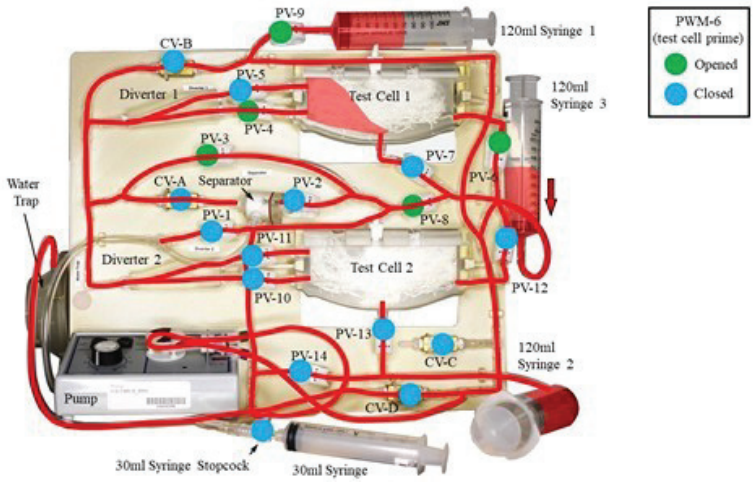

Figure 18. Prime Test Cell 1 from Inlet

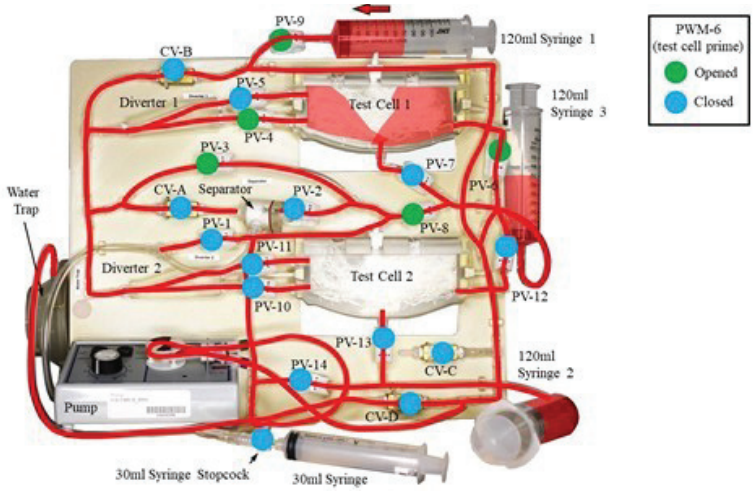

Figure 19. Prime Test Cell 1 from Outlet

3.4.2 Using Syringe 3, slowly prime Test Cell 1 inlet from the left (Figure 18).

3.4.3 Using Syringe 1, slowly prime Test Cell 1 outlet from the right (Figure 19).

3.4.4 Close PV-8, PV-9, PV-3, PV-4, and PV-6.

3.4.5 ✓**POIC** to ensure Test Cell 1 is properly primed

4. TEST CELL 2 PRIME

4.1 Open PV-13.

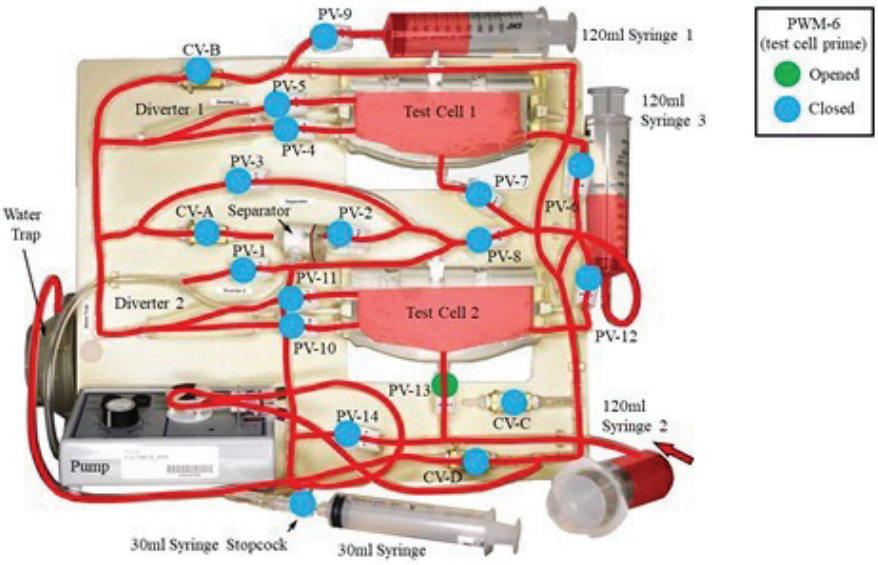

Figure 20. Prime Test Cell 2 through base

4.2 Using Syringe 2, slowly prime Test Cell 2, attempting to deliver the highest stable liquid volume possible with a single plunge, adjusting plunge rate as necessary (Figure 20).

4.3 Close PV-13.

4.4 ✓**POIC** to report Test Cell 2 fill level

If instructed,

4.4.1 Open PV-9, PV-10, and CV-B to full stop.

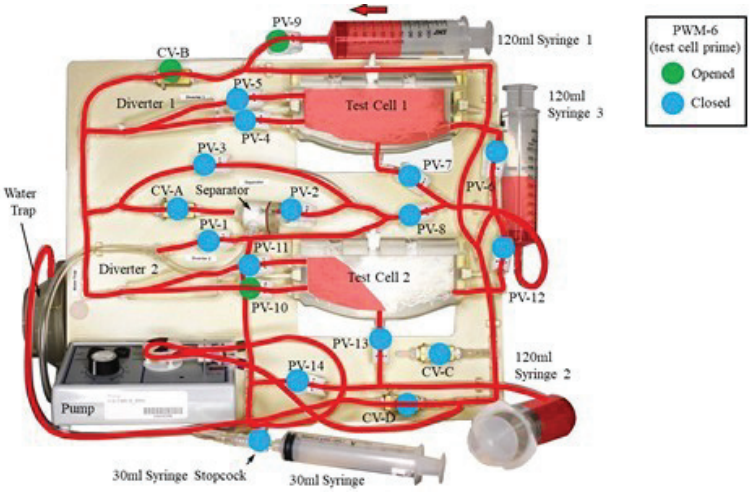

Figure 21. Prime Test Cell 2 from Inlet

4.4.2 Using Syringe 1, slowly prime Test Cell 2 inlet from the left (Figure 21).

4.4.3 Close PV-10 and CV-B.

4.4.4 Open PV-12.

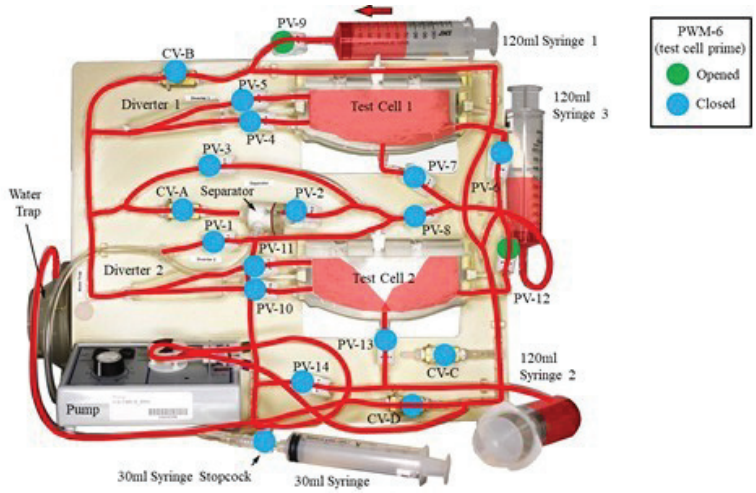

Figure 22. Prime Test Cell 2 from Outlet

4.4.5 Using Syringe 1, slowly prime Test Cell 2 outlet from the right (Figure 22).

4.4.6 Close PV-9 and PV-12.

4.4.7 ✓**POIC** to ensure Test Cell 2 is properly primed

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
PWM5_6-UHR-01	Hazardous Materials	CZ2/2	Go to step 1.5
PWM5_6-UHR-01	Hazardous Materials	CZ1/3	Go to step 1.7, step 1.8, step 1.9, step 1.10, step 1.11, step 1.12, and step 1.15
PWM5_6-UHR-01	Hazardous Materials	CZ1/4	Go to step 1.9

OBJECTIVE:

To add and remove liquid from Plant Water Management 6 Test Cell using various methods.

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA

1. EBB AND FLOW FROM TEST CELL 1 BASE

1.1 ✓NODE 2 Camcorder with close-up view of MWA still recording to 256GB SD Card (two)

1.2 ✓VOX configured for sound for hands-free communication

1.3 ✓Plant Water Management 120ml Syringe (three) tick marks are in FOV

1.4 **On POIC GO**

Open PV-7.

✓All other valves are closed

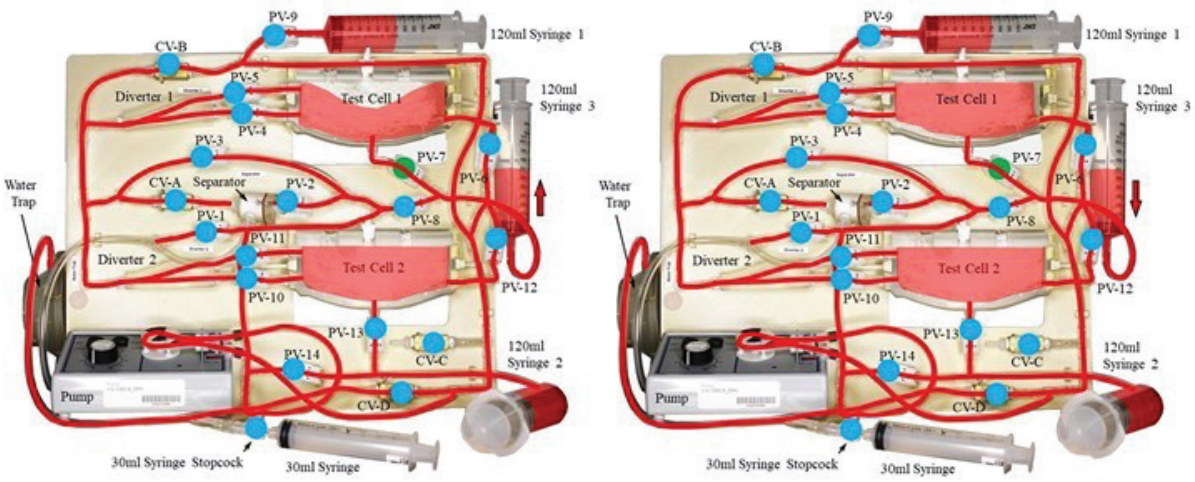

Figure 1. (a) Test Cell 1 Ebb / (b) Test Cell 1 Flow

1.5 Using Syringe 3, slowly withdraw as much liquid from Test Cell 1 as possible without ingesting bubbles (Figure 1a).

1.6 Using Syringe 3, slowly depress plunger to refill Test Cell 1 with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 1b).

1.7 Repeat step 1.5 and step 1.6 four more times.

1.8 Close PV-7.

1.9 ✓**POIC** once ebb and flow is completed

If instructed to complete ebb and flow for Test Cell 2,

1.9.1 Open PV-13.

✓All other valves are closed

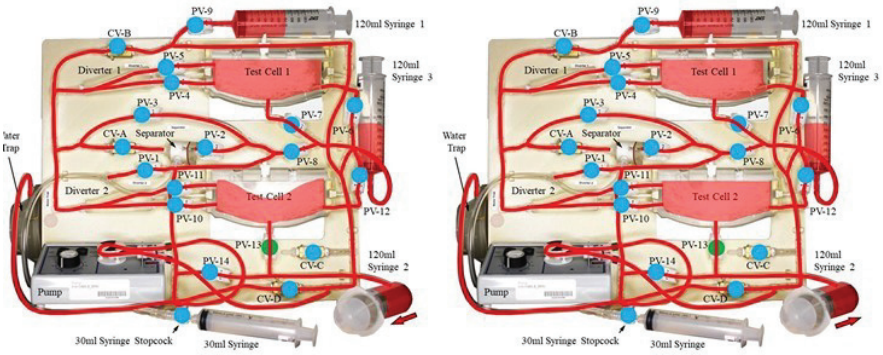

Figure 2. (a) Test Cell 2 Ebb / (b) Test Cell 2 Flow

1.9.2 Using Syringe 2, slowly withdraw as much liquid from Test Cell as possible without ingesting bubbles (Figure 2a).

1.9.3 Using Syringe 2, slowly depress plunger to refill Test Cell with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 2b).

1.9.4 Repeat step 1.9.2 and step 1.9.3 four more times.

1.9.5 Close PV-13.

2. EBB AND FLOW FROM TEST CELL 1 INLET

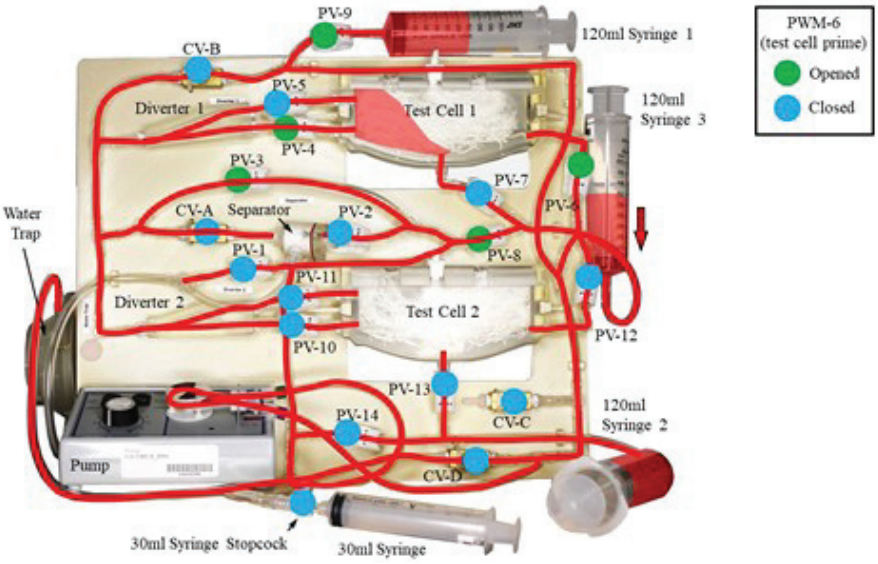

Figure 3. Ebb and Flow from Test Cell 1 Inlet

2.1 **On POIC GO**

Open PV-8, PV-3, PV-4, PV-6, and PV-9.

2.2 Using Syringe 3, slowly withdraw as much liquid from Test Cell 1 as possible without ingesting bubbles.

2.3 Using Syringe 3, slowly depress plunger to refill Test Cell 1 with as much liquid as possible to just below pinning edge without introducing bubbles.

2.4 Repeat step 2.2 and step 2.3.

3. EBB AND FLOW FROM TEST CELL 1 OUTLET

3.1 Using Syringe 1, slowly withdraw as much liquid as possible from Test Cell 1 without ingesting bubbles.

3.2 Using Syringe 1, slowly depress plunger to refill Test Cell 1 with as much liquid as possible to just below pinning edge without introducing bubbles.

3.3 Repeat step 3.1 and step 3.2.

3.4 Close PV-8, PV-3, PV-4, PV-6, and PV-9.

3.5 ✓**POIC** to report Syringe 1, Syringe 2, and Syringe 3 volumes

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
			Existing procedural hazard controls are not applicable to this procedure.

OBJECTIVE:

To test various forms of hydroponic flow throughout the Plant Water Management 6 system.

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA

1. TEST CELL 1 HYDROPONIC FLOW WITHOUT BUBBLES

1.1 ✓NODE 2 Camcorder with close-up view of MWA still recording to 256GB SD Card (two)

1.2 ✓VOX configured for sound for hands-free communication

1.3 ✓Plant Water Management 120ml Syringe (three) tick marks are in FOV

1.4 sw 120 VDC to 120 VAC Inverter SW2 → ON

1.5 Attach pump head tubing to pump head. Refer to Pump Tubing (00:16).

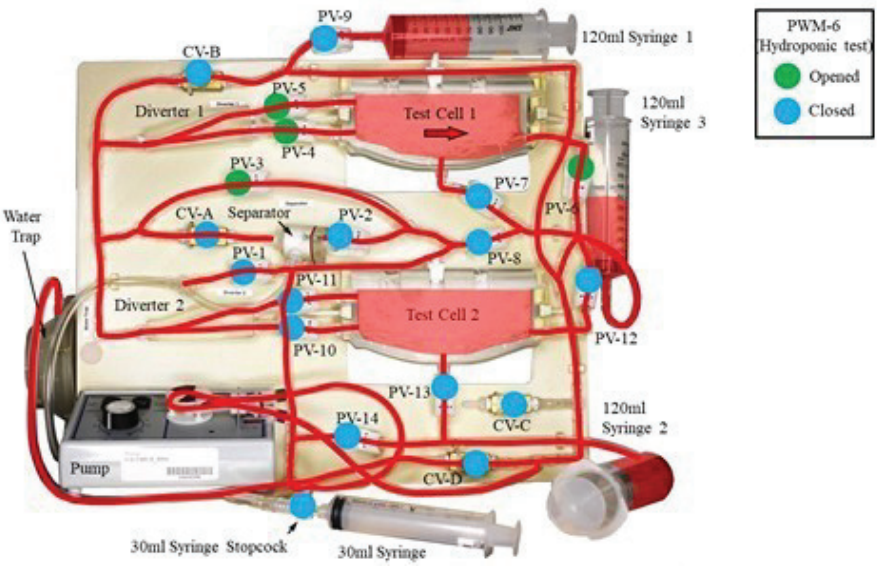

Figure 1. Test Cell 1 Hydroponics without Aeration

1.6 Open PV-3, PV-4, PV-5, and PV-6 (Figure 1).

1.7 ✓All other valves are closed

1.8 sw Flow Speed → SLOW (rocker switch middle position)

1.9 Turn Speed CTRL knob to 5.

1.10 sw Flow Direction → FORWARD (rocker switch bottom position)

1.11 Monitor hydroponic activity (approximately 20 minutes).

Adjust Speed CTRL knob as directed by **POIC**.

1.12 **On POIC GO**

Turn Speed CTRL knob CW by increments of 1, as instructed.

1.13 sw Flow Direction → OFF (rocker switch middle position)

Figure 2. CV Adjustment Rings

1.14 **On POIC GO**

Open PV-9 and CV-B (Figure 2).

Using Syringe 1, slowly add/remove liquid to Test Cell, as instructed.

Close PV-9 and CV-B.

1.15 ✓sw Flow Speed – SLOW (rocker switch middle position)

1.16 Turn Speed CTRL knob to 5.

1.17 sw Flow Direction → FORWARD (rocker switch bottom position)

1.18 **On POIC GO**

Turn Speed CTRL knob CW by increments of 1, as instructed.

1.19 sw Flow Direction → OFF (rocker switch middle position)

1.20 Repeat step 1.14 to step 1.19.

2. TEST CELL 1 HYDROPONIC FLOW WITH AERATION

2.1 ✓sw Flow Speed – SLOW (rocker switch middle position)

2.2 Turn Speed CTRL knob to 5.

2.3 sw Flow Direction → FORWARD (rocker switch bottom position)

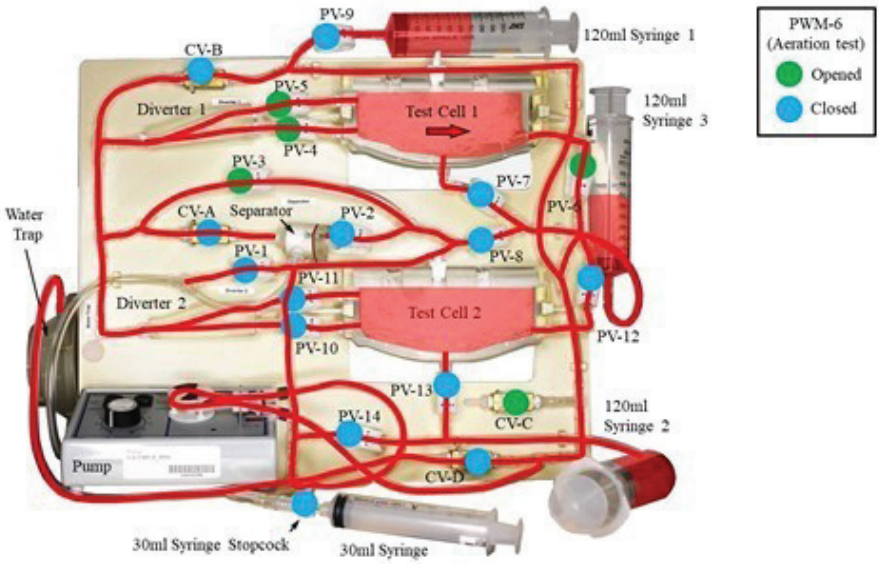

Figure 3. Test Cell 1 Hydroponics with Aeration

2.4 Slowly open CV-C by turning knob CCW until bubbles are ingested into the system (Figure 3).

2.5 ✓**POIC** for adjustments to CV-C and/or Pump

Observe bubble management of Diverter and Test Cell.

2.6 ✓**POIC** to add/remove liquid from Test Cell as instructed

2.7 Repeat step 2.5 and step 2.6 twice.

2.8 sw Flow Direction → OFF (rocker switch middle position)

2.9 ✓**POIC** to add/remove liquid from Test Cell as instructed

3. TEST CELL 1 AERATION, SEPARATION, AND WATER TRAP

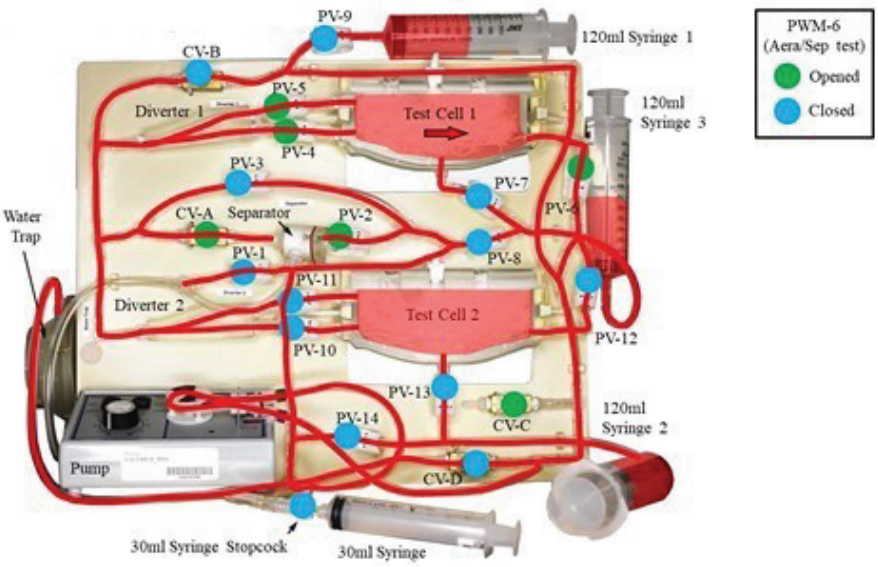

Figure 4. Test Cell 1 Hydroponics with Aeration, Separation, and Water Trap

3.1 Close PV-3 (Figure 4).

3.2 Open PV-2 and open CV-A to full stop (Figure 4).

3.3 ✓PV-4, PV-5, PV-6, and CV-C are open (Figure 4)

3.4 ✓Flow Speed – SLOW (rocker switch middle position)

3.5 ✓Speed CTRL – 5

3.6 sw Flow Direction → FORWARD (rocker switch bottom position)

3.7 ✓**POIC** for adjustments to CV-A, CV-C, and/or Pump

Observe bubble management of Diverter, Separator, and Water Trap for approximately 20 minutes.

3.8 **On POIC GO**

Open PV-9 and adjust CV-C as directed (Figure 2).

Add/remove liquid using Syringe 1 as directed.

Adjust Speed CTRL as directed.

3.9 ✓**POIC** for Plant Water Management 30ml Syringe use

Close CV-C.

Slowly withdraw plunger to fill 30ml Syringe with air.

Open 30ml Syringe Stopcock (handle parallel to tubing).

Using 30ml Syringe, slowly depress plunger, injecting bubbles into system.

Close 30ml Syringe Stopcock (handle perpendicular to tubing).

Refill 30ml Syringe with air, and repeat injection.

3.10 ✓**POIC** to report position of CV-A (Figure 2)

3.11 **On POIC GO**

sw Flow Direction → OFF (rocker switch middle position)

4. TEST CELL 2 HYDROPONICS

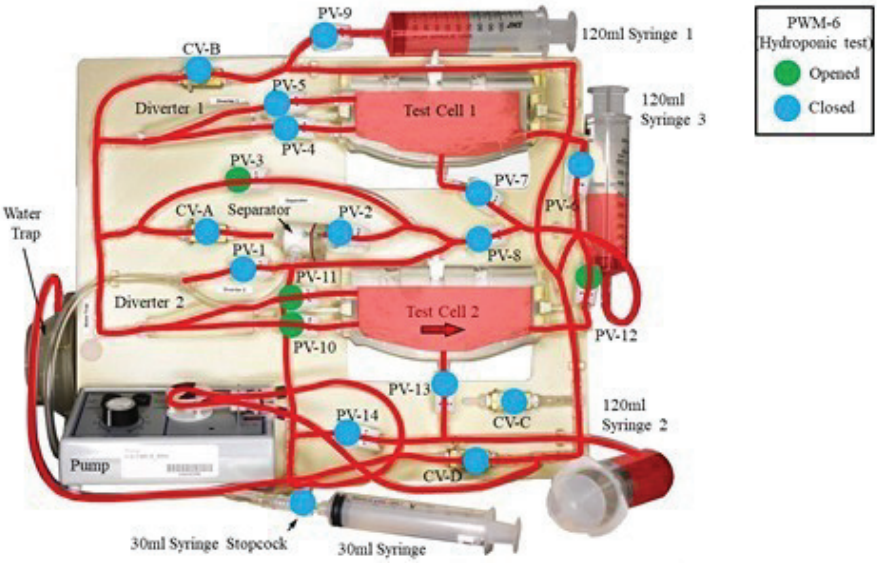

Figure 5. Test Cell 2 Hydroponics without Aeration

4.1 Open PV-3, PV-10, PV-11, and PV-12 (Figure 5).

4.2 ✓All other valves are closed

4.3 Repeat step 1.8 to step 1.20.

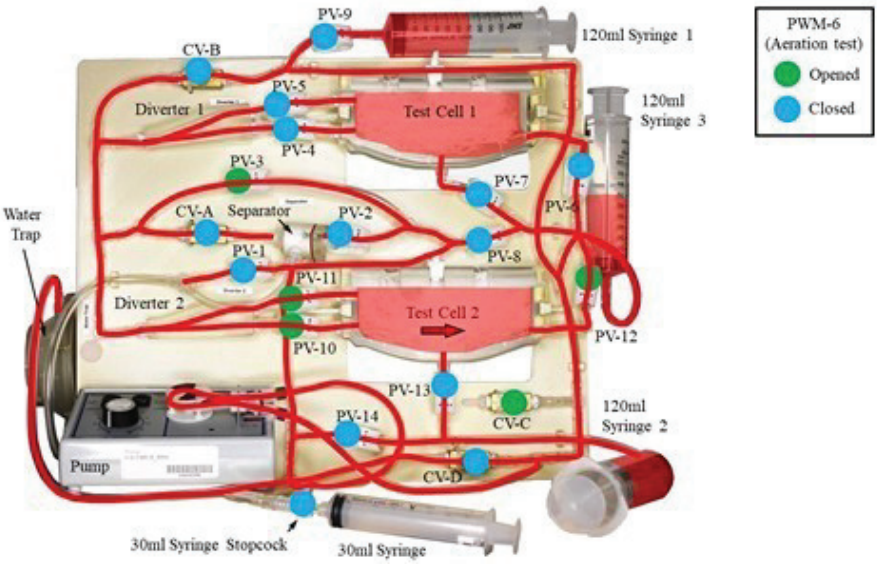

Figure 6. Test Cell 2 Hydroponics with Aeration

4.4 ✓PV-3, PV-10, PV-11, and PV-12 are open (Figure 6)

4.5 ✓All other valves are closed

4.6 Repeat step 2.

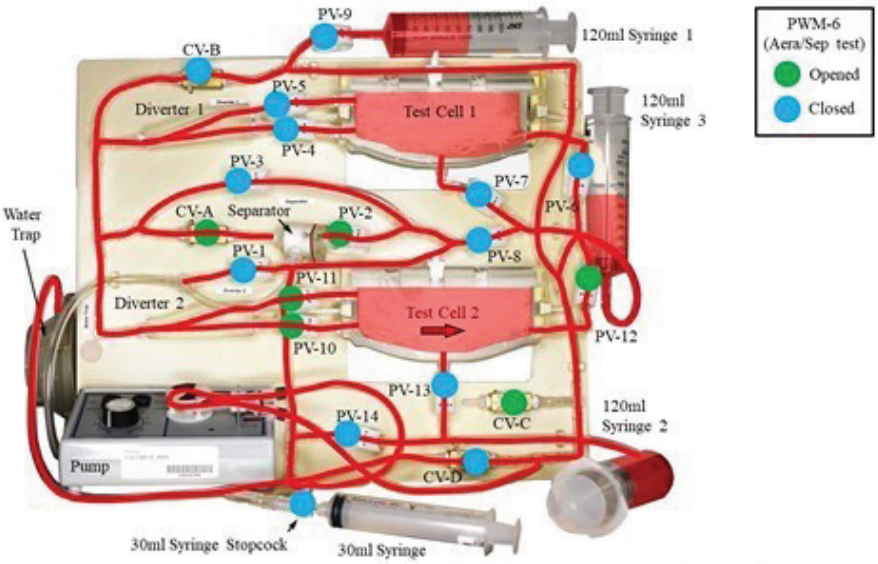

Figure 7. Test Cell 2 Hydroponics with Aeration, Separation, and Water Trap

4.7 Open PV-2 and CV-A to full stop (Figure 7).

4.8 ✓PV-10, PV-11, PV-12, and CV-C are open (Figure 7)

4.9 Repeat step 3.4 to step 3.11.

5. PARALLEL HYDROPONIC FLOW

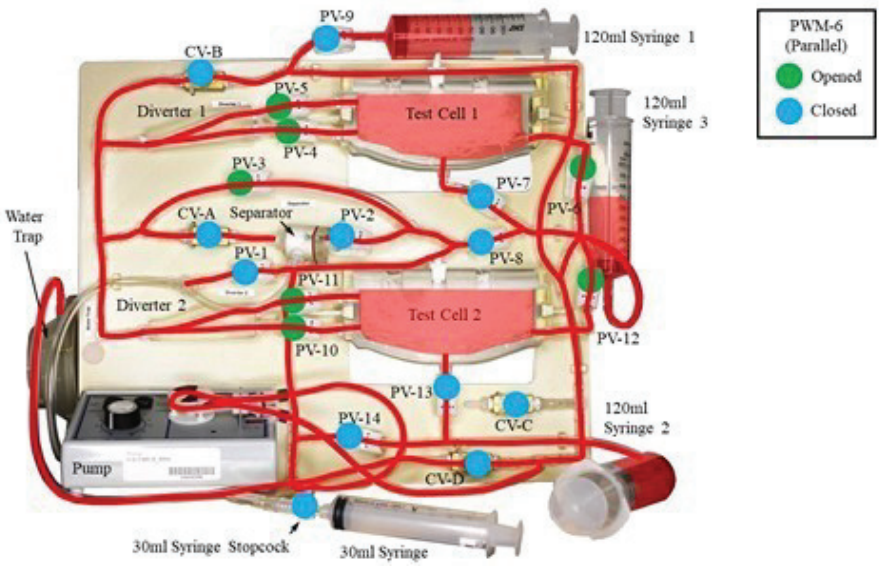

Figure 8. Parallel Hydroponic Flow

5.1 Open PV-3, PV-4, PV-5, PV-6, PV-10, PV-11, and PV-12 (Figure 8).

5.2 ✓All other valves are closed

5.3 ✓**POIC** for Test Cell fill level

5.4 ✓Flow Speed – SLOW (rocker switch middle position)

5.5 ✓Speed CTRL – 5

5.6 sw Flow Direction → FORWARD (rocker switch bottom position)

5.7 Monitor hydroponic flow (approximately 20 minutes).

Adjust pump settings, valve positions, and fill level of Test Cells as directed by **POIC** (Figure 2).

6. PARALLEL HYDROPONIC FLOW WITH AERATION

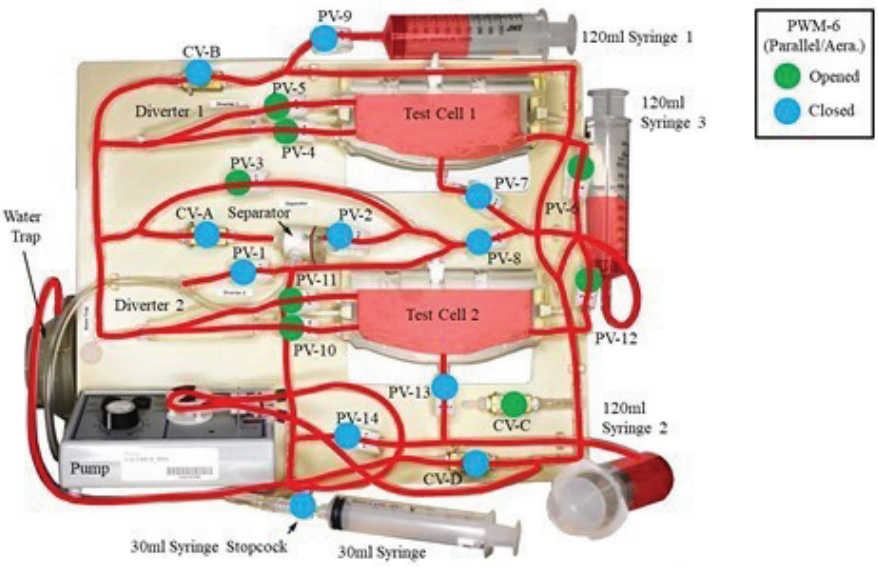

Figure 9. Parallel Hydroponic Flow with Aeration

6.1 Slowly open CV-C by turning knob CCW until bubbles are ingested into the system (Figure 9).

6.2 ✓**POIC** for adjustments to CV-C, PV positions, and Test Cell fill levels (Figure 2)

7. PARALLEL HYDROPONICS WITH AERATION, SEPARATION, AND WATER TRAP

7.1 sw Flow Direction → OFF (rocker switch middle position)

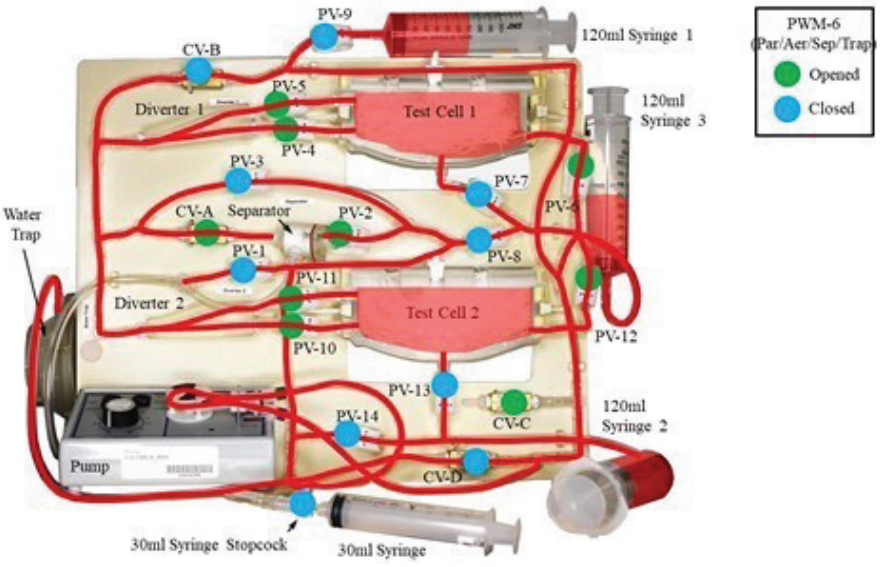

Figure 10. Parallel Hydroponics with Aeration, Separation, and Trap

7.2 Open PV-2 and CV-A to full stop (Figure 10).

7.3 Close PV-3 (Figure 10).

7.4 ✓Flow Speed – SLOW (rocker switch middle position)

7.5 ✓Speed CTRL – 5

7.6 sw Flow Direction → FORWARD (rocker switch bottom position)

7.7 ✓**POIC** for adjustments to CV-A, CV-C, and/or Pump

Observe and bubble management of Diverter, Separator, and Water Trap for approximately 20 minutes.

7.8 sw Flow Direction → OFF (rocker switch middle position)

7.9 Close CV-C, CV-A, and PV-2.

7.10 Remove pump head tubing from pump head. Refer to Pump Tubing (00:16).

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
			Existing procedural hazard controls are not applicable to this procedure.

OBJECTIVE:

To spot check the Plant Water Management Test Cells through ebb and flow.

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA

1. EBB AND FLOW FROM TEST CELL 1 BASE

1.1 ✓NODE 2 Camcorder with close-up view of MWA still recording to 256GB SD Card (two)

1.2 ✓VOX configured for sound for hands-free communication

1.3 ✓Plant Water Management 120ml Syringe (three) tick marks are in FOV

1.4 **On POIC GO**

Open PV-7.

✓All other valves are closed

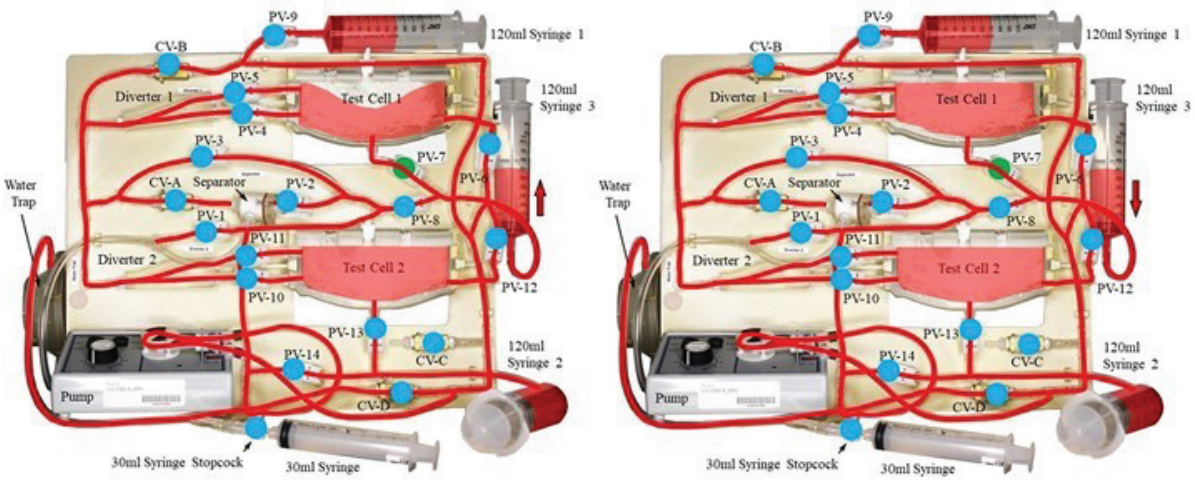

Figure 1. (a) Test Cell 1 Ebb / (b) Test Cell 1 Flow

1.5 Using Syringe 3, slowly withdraw as much liquid as possible from Test Cell 1 without ingesting bubbles (Figure 1a).

1.6 Using Syringe 3, slowly depress plunger to refill Test Cell 1 with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 1b).

1.7 Repeat step 1.5 to step 1.6 three more times.

1.8 Close PV-7.

2. EBB AND FLOW FROM TEST CELL 1 INLET AND OUTLET

2.1 Open PV-8, PV-3, PV-4, PV-6, and PV-9.

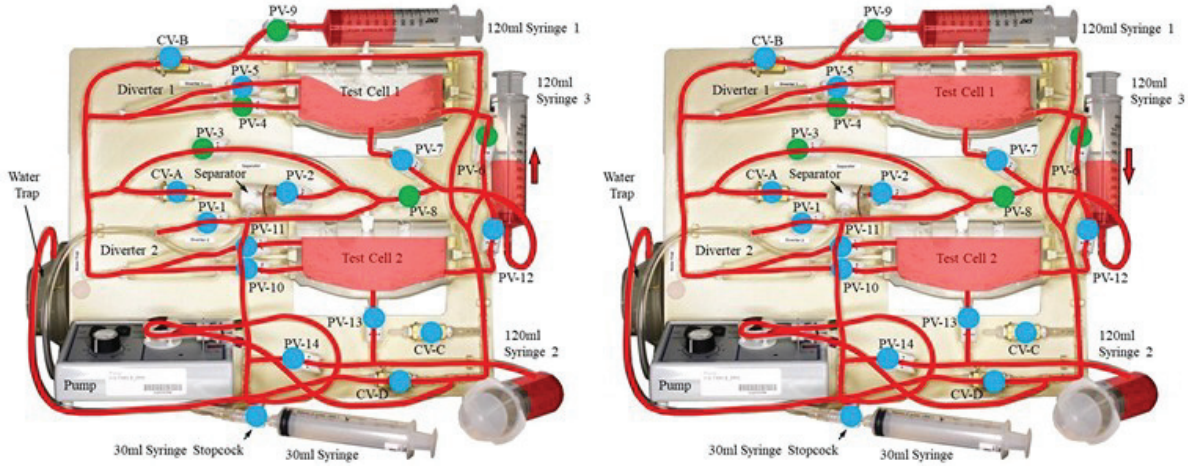

Figure 2. (a) Test Cell 1 Ebb from Inlet / (b) Test Cell 1 Flow from Inlet

2.2 Using Syringe 3, slowly withdraw as much liquid as possible from Test Cell 1 without ingesting bubbles (Figure 2a).

2.3 Using Syringe 3, slowly depress plunger to refill Test Cell 1 with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 2b).

2.4 Repeat step 2.2 to step 2.3.

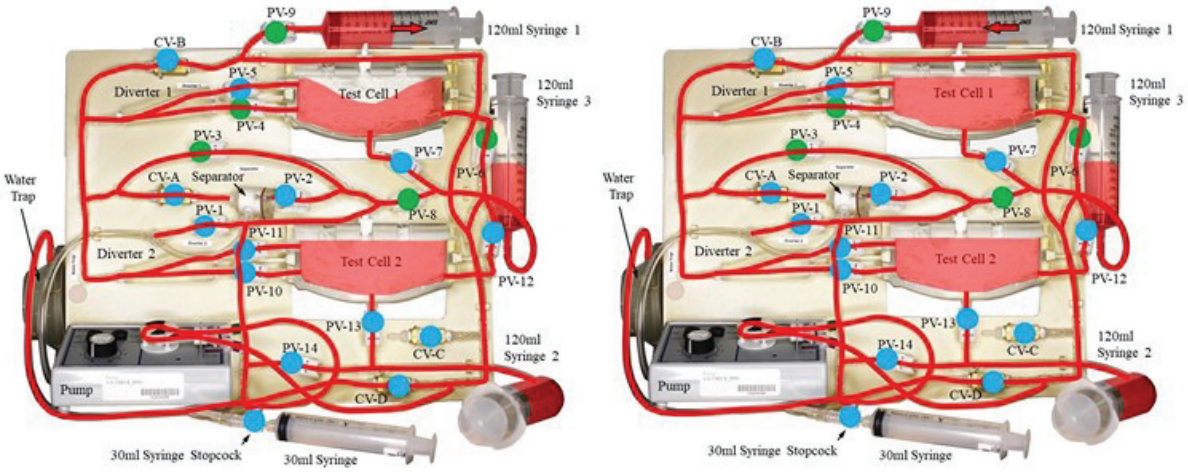

Figure 3. (a) Test Cell 1 Ebb from Outlet / (b) Test Cell 1 Flow from Outlet

2.5 Using Syringe 1, slowly withdraw as much liquid as possible from Test Cell 1 without ingesting bubbles (Figure 3a).

2.6 Using Syringe 1, slowly depress plunger to refill Test Cell 1 with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 3b).

2.7 Repeat step 2.5 to step 2.6.

3. EBB AND FLOW FROM TEST CELL 2 BASE

3.1 Close all valves.

3.2 ✓Plant Water Management 120ml Syringe (three) tick marks are in FOV

3.3 Open PV-13.

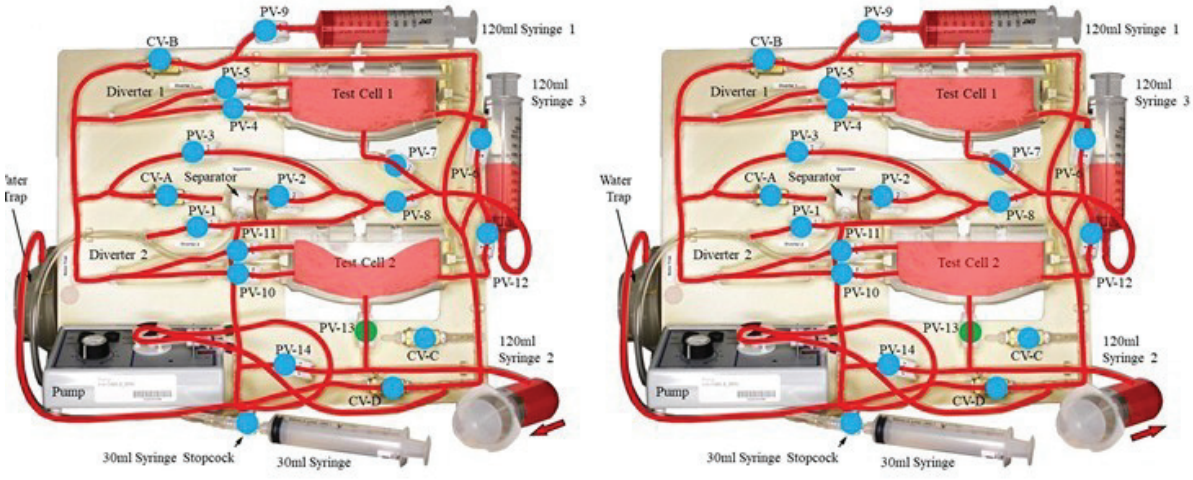

Figure 4. (a) Test Cell 2 Ebb from Base / (b) Test Cell 2 Flow through Base

3.4 Using Syringe 2, slowly withdraw as much liquid as possible from Test Cell 2 without ingesting bubbles (Figure 4a).

3.5 Using Syringe 2, slowly depress plunger to refill Test Cell 2 with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 4b).

3.6 Repeat step 3.4 to step 3.5 three more times.

3.7 Close PV-13.

4. EBB AND FLOW FROM TEST CELL 2 INLET AND OUTLET

4.1 Open PV-3, PV-8, PV-10, PV-9, and PV-12.

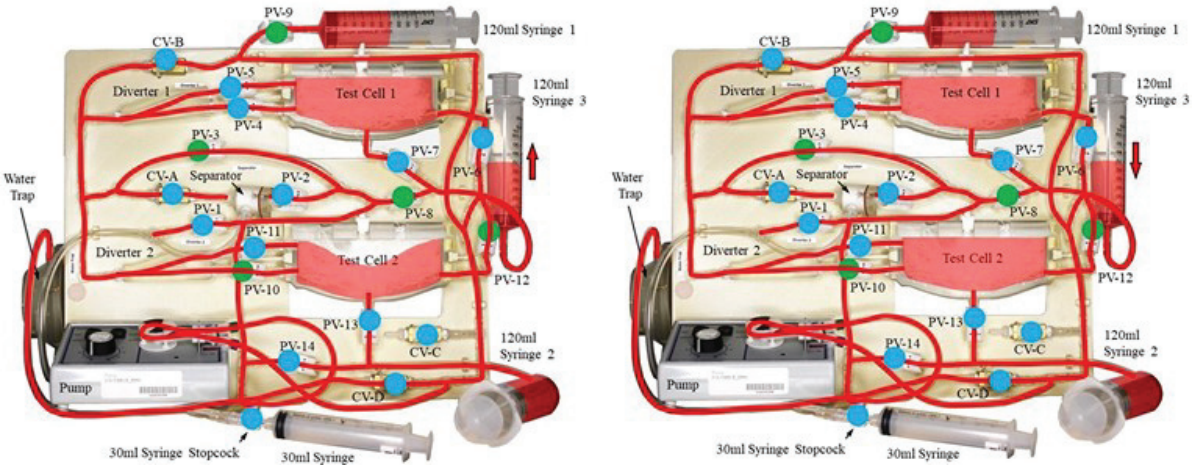

Figure 5. (a) Test Cell 2 Ebb from Inlet / (b) Test Cell 2 Flow from Inlet

4.2 Using Syringe 3, slowly withdraw as much liquid as possible from Test Cell 2 inlet without ingesting bubbles (Figure 5a).

4.3 Using Syringe 3, slowly depress plunger to refill Test Cell 2 through inlet with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 5b).

4.4 Repeat step 4.2 to step 4.3.

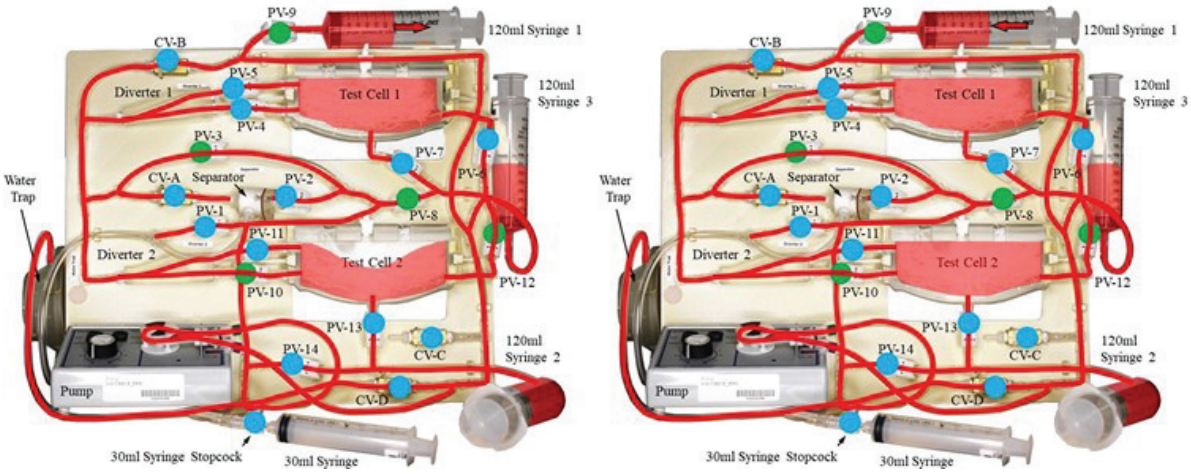

Figure 6. (a) Test Cell 2 Ebb from Outlet / (b) Test Cell 2 Flow from Outlet

4.5 Using Syringe 1, slowly withdraw as much liquid as possible from Test Cell 2 outlet without ingesting bubbles (Figure 6a).

4.6 Using Syringe 1, slowly depress plunger to refill Test Cell 2 through outlet with as much liquid as possible to just below pinning edge without introducing bubbles (Figure 6b).

4.7 Repeat step 4.5 to step 4.6.

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
			Existing procedural hazard controls are not applicable to this procedure.

Parameters 1. Root Replacement

Root Test	Root Remove	Root Replace
[generic]	[remove]	[replace]
Root Test 1	Plant Water Management Root Type 4	Plant Water Management Root Type 1
Root Test 2	Plant Water Management Root Type 1	Plant Water Management Root Type 2
Root Test 3	Plant Water Management Root Type 2	Plant Water Management Root Type 3

OBJECTIVE:

To test root models to imitate various absorption rates and plant sizes.

PARTS:

Plant Water Management Root Kit P/N PWM5617:

Plant Water Management Root Type 1 P/N PWM5617-01 (six)
Plant Water Management Root Type 2 P/N PWM5617-02 (six)
Plant Water Management Root Type 3 P/N PWM5617-03 (six)

MATERIALS:

Dry Wipes (as needed)
Ziplock Bag

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA

1. TEST CELL 1 DRAIN

1.1 ✓NODE 2 Camcorder with close-up view of MWA still recording to 256GB SD Card (two)

1.2 ✓VOX configured for sound for hands-free communication

1.3 ✓Plant Water Management 120ml Syringe (three) tick marks are in FOV

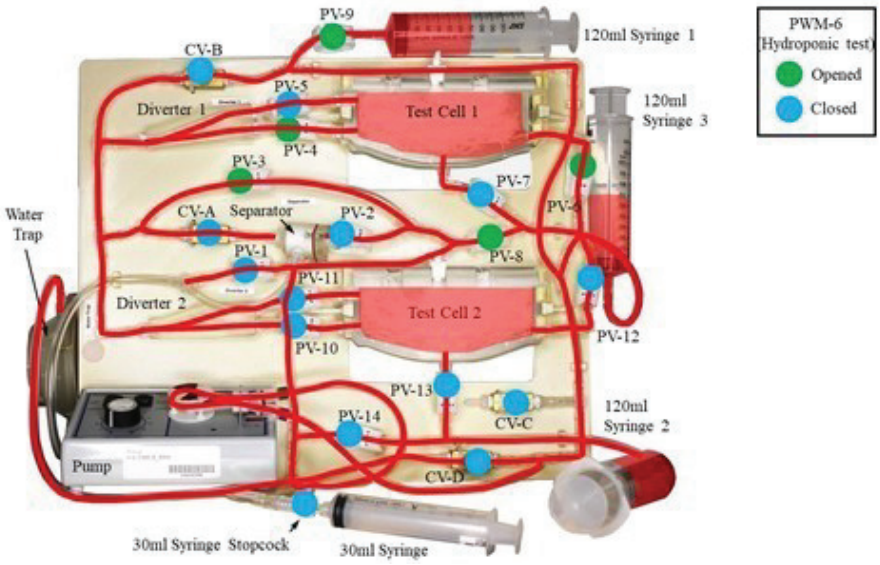

Figure 1. Prep for Test Cell 1 Drain

1.4 Open PV-8, PV-3, PV-4, PV-6, and PV-9 (Figure 1).

1.5 ✓All other valves are closed

1.6 ✓**POIC** to report Plant Water Management 120ml Syringe (three) volumes

1.7 Using Syringe 1 and Syringe 3, slowly withdraw as much liquid as possible from Test Cell 1 without ingesting bubbles.

1.8 ✓**POIC** to report Test Cell 1 volume

If further draining needed,

Close PV-8, PV-3, PV-4, PV-6, and PV-9.

Open PV-7.

Using Syringe 3, slowly withdraw as much liquid as possible from the base of the Test Cell 1 without ingesting bubbles.

Close PV-7.

2. TEST CELL 2 DRAIN

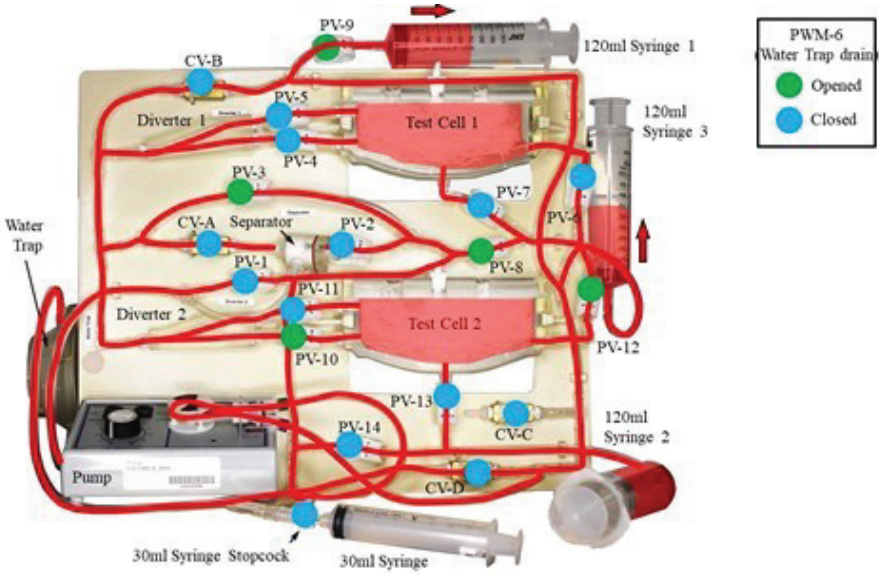

Figure 2. Prep for Test Cell 2 Drain

2.1 Open PV-3, PV-8, PV-9, PV-10, and PV-12 (Figure 2).

2.2 ✓All other valves are closed

2.3 ✓**POIC** to report Plant Water Management 120ml Syringe (three) volumes

2.4 Using Syringe 1 and Syringe 3, slowly withdraw as much liquid as possible from Test Cell 2 without ingesting bubbles.

2.5 ✓**POIC** to report Test Cell 2 volume

If further draining needed,

> Close PV-3, PV-8, PV-9, PV-10, and PV-12.
>
> Open PV-13.
>
> Using Syringe 2, slowly withdraw as much liquid as possible from the base of Test Cell 2 without ingesting bubbles.
>
> Close PV-13.

3. ROOT REMOVAL

3.1 Open Test Cell lid by pulling tab. Refer to Root Remove (00:20).

Gently remove **[remove]** from Test Cell 1 and place in Ziplock Bag [Dry Wipes].

3.2 Repeat step 3.1 for Test Cell 2.

3.3 Discard Ziplock Bag containing Dry Wipes and **[remove]**.

4. ROOT TESTS

4.1 Insert stem of **[replace]** into one of the slots on Test Cell 1 lid. Refer to Root Replace (00:53).

Gently guide roots inside and center beneath the stem.

4.2 Repeat step 4.1 to insert **[replace]** into remaining open slots of Test Cell 1.

4.3 Repeat step 4.1 and step 4.2 for Test Cell 2.

4.4 ✓**POIC** for steps to perform

Per **POIC** PD instruction,

> Complete steps for Ebb and Flow and Hydroponics.
>
> Perform 2.029 PLANT WATER MANAGEMENT 6 EBB AND FLOW, per PD direction (US PODF: Plant Water Management 5&6)
>
> Perform 2.030 PLANT WATER MANAGEMENT 6 HYDROPONIC FLOW, per PD direction (US PODF: Plant Water Management 5&6)

4.5 ✓Remove pump head tubing from pump head. Refer to Pump Tubing (00:16).

Ground should update IMS for the following parts:

Plant Water Management Root Type 1 P/N PWM5617-01 (three) TO: Temp stow in Ziplock Bag (step 3.3)

Plant Water Management Root Type 2 P/N PWM5617-02 (three) TO: Temp stow in Ziplock Bag (step 3.3)

Plant Water Management Root Type 3 P/N PWM5617-03 (three) TO: installed (step 3.3)

Plant Water Management Root Type 4 P/N PWM5617-04 (three) TO: Temp stowed in Ziplock Bag (step 3.3)

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
PWM5_6-UHR-01	Hazardous Materials	CZ1/3	Go to step 3.1 and step 3.3
STD-PWM-01	Hazardous Materials	CTL-6/6.2	Go to step 3.1

2.033 PLANT WATER MANAGEMENT 6 LIMITS TEST

(PB3-01-2890) Page 1 of 6 pages

OBJECTIVE:

To test performance limits of the Separator and Water Trap.

MATERIALS:

Dry Wipe (if needed)

Ziplock Bag (if needed)

NOTE

1. This NOTE is for the entire procedure.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

MWA

1. SEPARATOR LIMITS

1.1 ✓NODE 2 Camcorder with close-up view of MWA still recording to 256GB SD Card (two)

1.2 ✓VOX configured for sound for hands-free communication

1.3 ✓Plant Water Management 120ml Syringe (three) tick marks are in FOV

Figure 1. CV Adjustment Rings

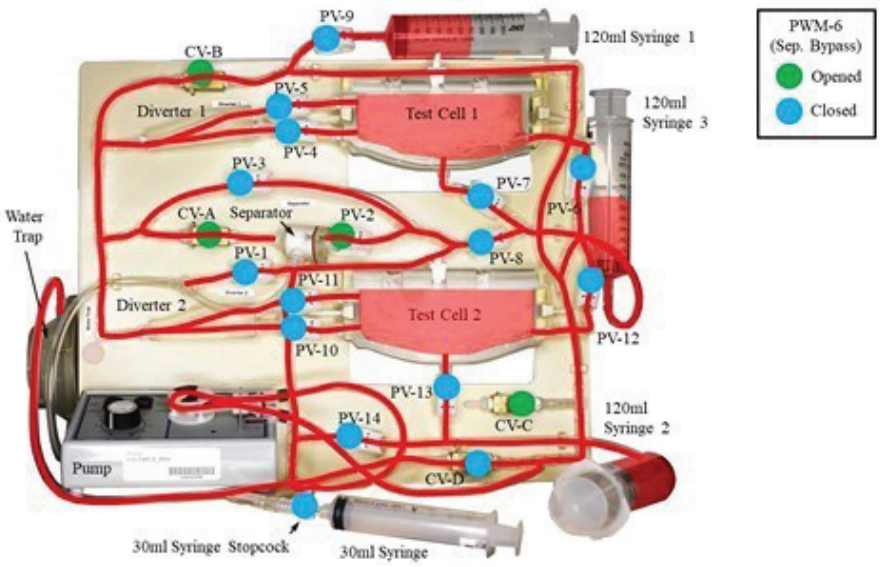

Figure 2. Separator Limits Bypass Test

1.4 ✓**POIC** for CV setpoints (Figure 1)

Open CV-C as instructed.

1.5 Open PV-2 (Figure 2).

Open CV-A and CV-B to full stop.

1.6 ✓All other valves are closed

1.7 Attach pump head tubing to pump head. Refer to Pump Tubing (00:16).

1.8 sw Flow Speed → SLOW (rocker switch middle position)

1.9 Turn Speed CTRL knob to 5.

1.10 sw Flow Direction → FORWARD (rocker switch bottom position)

1.11 ✓**POIC** to establish steady states by adjusting CV-C, CV-A, and/or Pump

If significant water, about 10mL, enters Water Trap,

sw Flow Direction → OFF (rocker switch middle position)

1.12 **On POIC GO**

sw Flow Direction → OFF (rocker switch middle position)

2. SEPARATOR LIMITS WITH PARALLEL TEST CELL FLOW

2.1 ✓**POIC** to report Test Cell fill levels

If instructed,

~

~

Open PV-7 and PV-13.

Using Syringe 3, slowly depress plunger to fill Test Cell 1.

Using Syringe 2, slowly depress plunger to fill Test Cell 2.

Close PV-7 and PV-13.

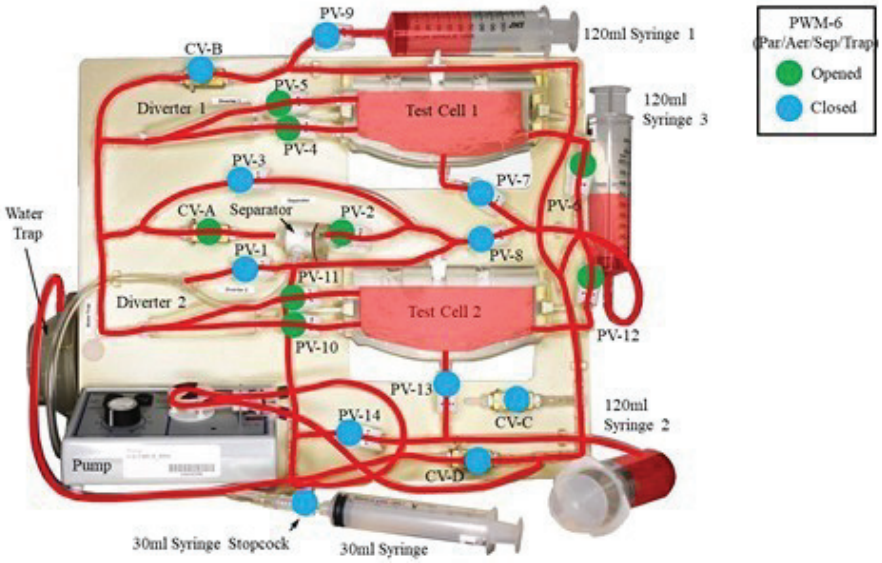

Figure 3. Separator Limits Test through Test Cells

2.2 Close CV-B and CV-C (Figure 3).

2.3 Open PV-4, PV-5, PV-6, PV-10, PV-11, and PV-12 (Figure 3).

2.4 ✓PV-2 open

✓CV-A open to full stop

2.5 ✓All other valves are closed

2.6 ✓sw Pump Speed – SLOW (rocker switch middle position)

2.7 ✓Speed CTRL – 5

2.8 sw Flow Direction → FORWARD (rocker switch bottom position)

2.9 ✓**POIC** to establish steady states by adjusting CV-C, CV-A, and/or Pump

If significant water, about 10mL, enters Water Trap,

sw Flow Direction → OFF (rocker switch middle position)

2.10 **On POIC GO**

sw Flow Direction → OFF (rocker switch middle position)

3. WATER TRAP LIMITS

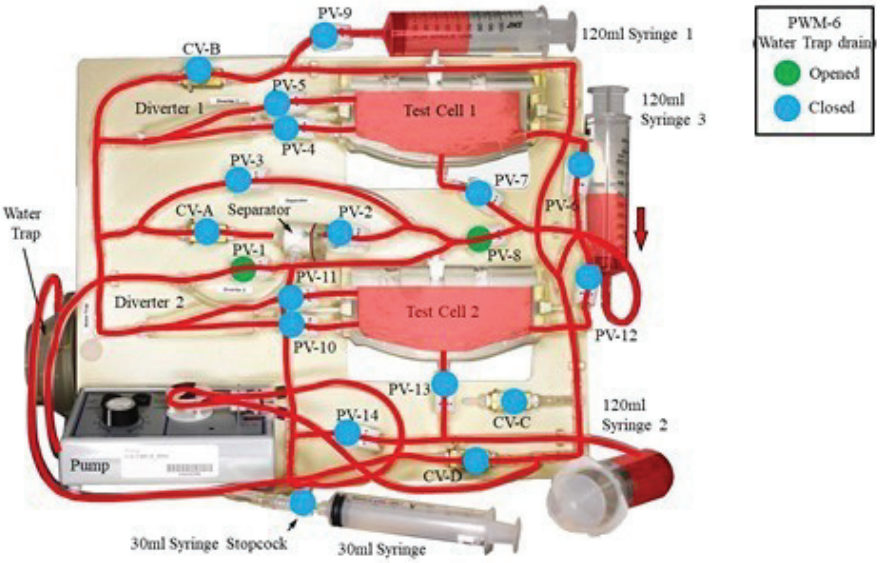

Figure 4. Fill Water Trap through Inlet

3.1 Open PV-1 and PV-8 (Figure 4).

3.2 ✓All other valves are closed

3.3 Using Syringe 3, slowly depress plunger to add 5ml to Water Trap.

3.4 Close PV-1 and PV-8.

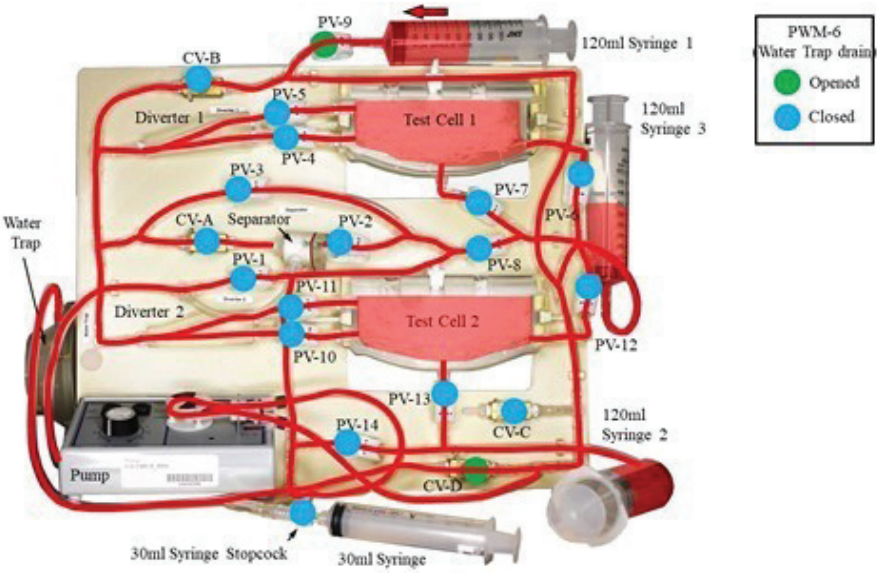

Figure 5. Fill Water Trap through Outlet

3.5 Open PV-9 and CV-D to full stop (Figure 5).

3.6 Using Syringe 1, slowly depress plunger to add 5ml to Water Trap.

3.7 Close PV-9.

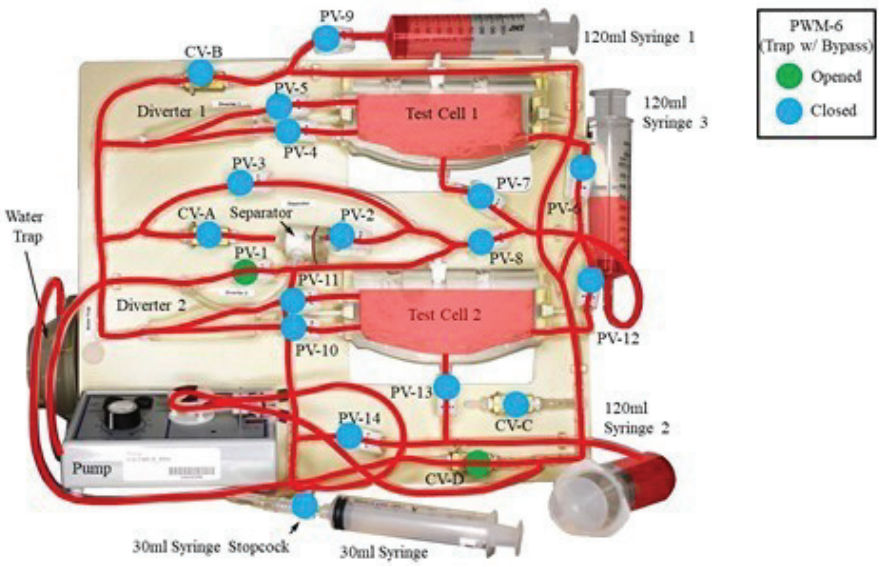

Figure 6. Water Trap Limit Test through Bypass

3.8 Open PV-1 (Figure 6).

3.9 Open 30ml Syringe Stopcock (handle parallel to tubing).

3.10 Using Plant Water Management 30ml Syringe, ingest 30ml of air.

3.11 Close 30ml Syringe Stopcock (handle perpendicular to tubing).

3.12 sw Flow Speed → FAST (rocker switch bottom position)

3.13 Turn Speed CTRL knob to 5.

3.14 sw Flow Direction → FORWARD (rocker switch bottom position)

3.15 ✓**POIC** to establish steady states

If significant water, about 10ml, enters Water Trap, or if droplets appear on outside of Water Trap,

sw Flow Direction → OFF (rocker switch middle position)

Gently remove any liquid on the outside of the Water Trap using Dry Wipe.

Place used Dry Wipe in Ziplock Bag. Discard.

3.16 ✓**POIC** to inject air

Using 30ml Syringe, slowly introduce small and large, single and multiple bubbles into the system.

3.17 Close 30ml Syringe Stopcock (handle perpendicular to tubing).

3.18 **On POIC GO**

sw Flow Direction → OFF (rocker switch middle position)

3.19 Open PV-8.

3.20 Using Syringe 3, add 5ml of liquid.

3.21 Close PV-8.

3.22 ✓**POIC** for further instruction

If instructed,

Repeat step 3.14 to step 3.18.

3.23 Remove pump head tubing from pump head. Refer to Pump Tubing (00:16).

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
PWM5_6-UHR-01	Hazardous Materials	CZ1/3	Go to step 3.15

2.034 PLANT WATER MANAGEMENT 6 TEARDOWN AND STOW

(PB3-01-2890 / IMPACT S) Page 1 of 6 pages

OBJECTIVE:

To drain Plant Water Management 6, trash, and stow necessary hardware.

NOTE

1. This NOTE applies to steps 1-3.
2. This procedure requires Real-time video downlinked using both Node 2 Camcorders during AOS. The science operations will be continuously recorded onto SD cards using the second Node 2 Camcorder. Recorded science video will be downlinked at a later time.
3. The internal Camcorder Microphone will be used to record audio of pump and fluid movement. To disable audio when not needed, refer to 1.202 XF705 CAMCORDER BUILT-IN MIC ACTIVATION, step 3 (US SODF:PhotoTV:1. Canon XF705)
4. Vox Mode is required for hands-free communication.

NOD2S4 1. WATER TRAP DRAIN

1.1 ✓NODE 2 Camcorder with close-up view of MWA still recording to 256GB SD Card (two)

1.2 ✓VOX configured for sound for hands-free communication

1.3 ✓Plant Water Management 120ml Syringe (three) tick marks are in FOV

1.4 ✓All valves are closed

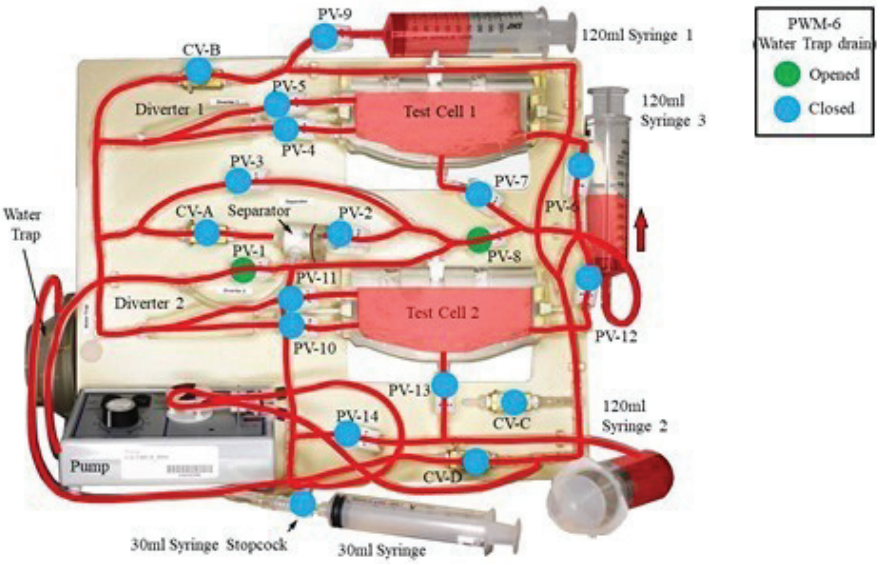

Figure 1. Drain Water Trap from Inlet

1.5 Open PV-1 and PV-8 (Figure 1).

1.6 Using Syringe 3, slowly remove liquid from Water Trap to Y-fitting downstream of PV-8 (Figure 1).

1.7 Close PV-1 and PV-8.

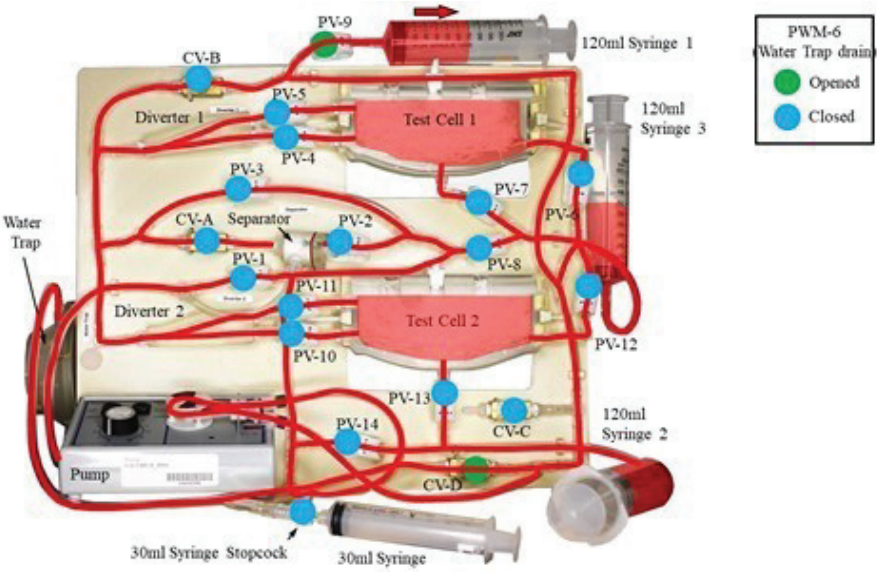

Figure 2. Drain Water Trap from Outlet

1.8 Open PV-9 and CV-D to full stop (Figure 2).

1.9 Using Syringe 1, slowly remove liquid from Water Trap to CV-D (Figure 2).

1.10 Close PV-9 and CV-D to full stop.

2. TEST CELL 1 DRAIN

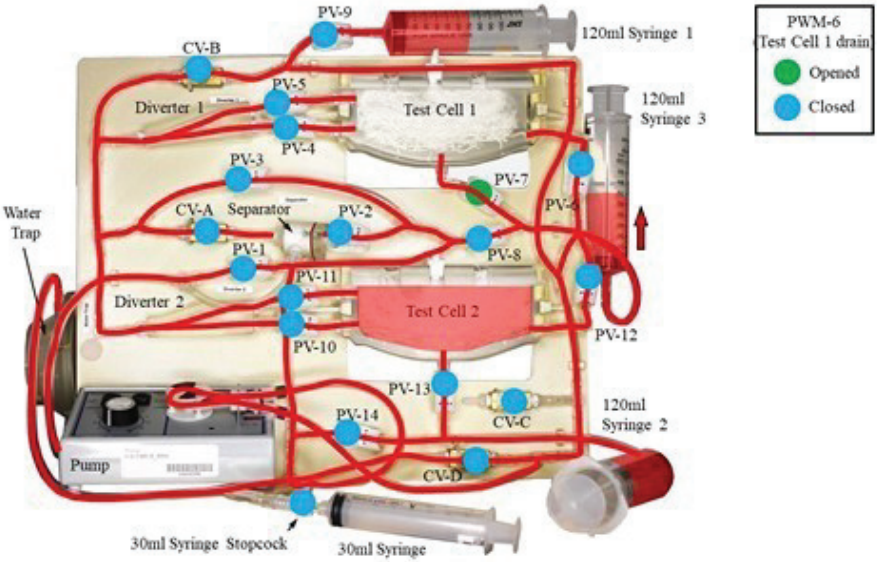

Figure 3. Drain Test Cell 1

2.1 Open PV-7 (Figure 3).

2.2 Using Syringe 3, rapidly remove 50ml of liquid from Test Cell 1 (Figure 3).

2.3 Using Syringe 3, rapidly add 50ml of liquid back into Test Cell 1.

2.4 Repeat step 2.2 and step 2.3.

2.5 **On POIC GO**

Using Syringe 3, slowly remove all remaining liquid from Test Cell 1 without ingesting bubbles.

2.6 Close PV-7.

2.7 Open Test Cell lid by pulling tab. Refer to Root Remove (00:20).

Gently remove Plant Water Management Root Type 3 (three) from Test Cell [Dry Wipe].

2.8 Place Plant Water Management Root Type 3 (three) and used Dry Wipes in Ziplock Bag. Temp stow.

3. TEST CELL 2 DRAIN

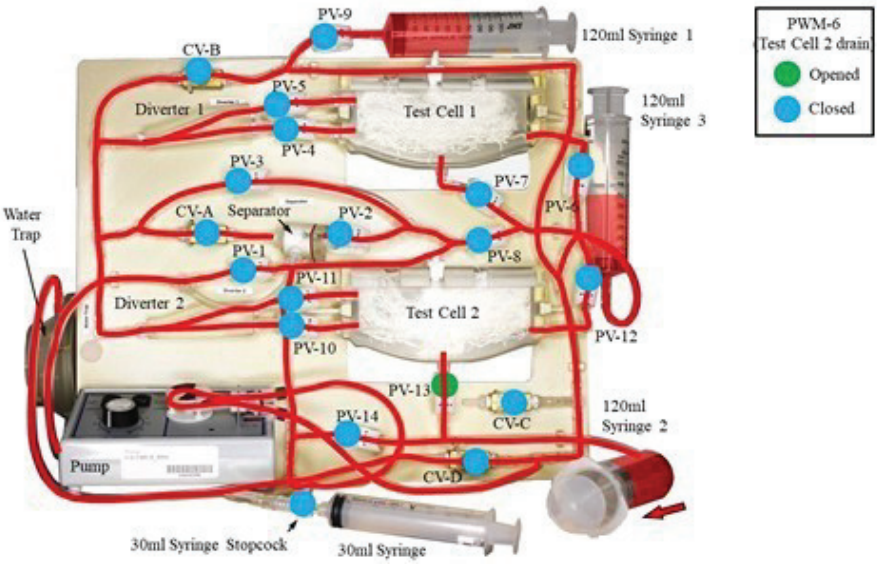

Figure 4. Drain Test Cell 2

3.1 Open PV-13 (Figure 4).

3.2 Using Syringe 2, rapidly remove 50ml of liquid from Test Cell 2 (Figure 4).

3.3 Using Syringe 2, rapidly add 50ml of liquid back into Test Cell 2.

3.4 Repeat step 3.2 and step 3.3.

3.5 **On POIC GO**

Using Syringe 2, slowly remove all remaining liquid from Test Cell 2 without ingesting bubbles.

3.6 Close PV-13.

3.7 Open Test Cell lid by pulling tab. Refer to Root Remove (00:20).

Gently remove Plant Water Management Root Type 3 (three) from Test Cell [Dry Wipe].

3.8 Place Plant Water Management Root Type 3 (three) and used Dry Wipes in Ziplock Bag. Temp stow.

3.9 Doff VOX.

4. PLANT WATER MANAGEMENT 6 TEARDOWN

4.1 sw 120 VDC to 120 VAC Inverter SW2 → OFF (S/N 1038)

4.2 Power Cable ←|→ Inverter GFCI Cable 3'

4.3 AWS Snowcone Power Supply →|← Inverter GFCI Cable 3'

4.4 Pump ←|→ Power Cable

4.5 ✓Pump head tubing is removed from pump head

4.6 Remove Pump.

Discard Gray Tape.

4.7 Temp stow Pump and Power Cable.

4.8 ✓All valves are closed

Figure 5. Plant Water Management 6 Mounting Points

4.9 Remove Plant Water Management 6 [#10 Fasteners] (Figure 5).

4.10 Discard Plant Water Management 6 and Ziplock Bags containing Plant Water Management Root Type 3 (six) and used Dry Wipes.

4.11 sw LED Work Light (two) → OFF

4.12 sw 120 VDC to 120 VAC Inverter SW3 → OFF (S/N 1038)

4.13 Work Light USB Power Cable (two) ←|→ Multi-Port USB Charger

4.14 Work Light USB Power Cable (two) ←|→ LED Work Light (two)

4.15 Remove LED Work Light (two) from Flexible Bracket (two).

4.16 Remove Flexible Bracket (two) from Seat Track.

4.17 Remove A-4 Printer Paper from Laptop Desk. Discard.

4.18 Remove Laptop Desk from Multi-Use Bracket.

4.19 Remove Multi-Use Bracket from Seat Track.

5. CAMCORDER RECONFIGURATION

NODE2 Cam 2

5.1 Stop recording to 256GB SD Card (two) on second NODE2 Camcorder with close-up view of MWA.

5.2 AUDIO SETUP

5.2.1 pb MENU → Press

5.2.2 Joystick → '  **Audio Select**'

5.2.3 Joystick → Press

5.2.4 Joystick → '**Select CH1/CH2 Input**'

5.2.5 Joystick → Press

5.2.6 Joystick → '**Input Terminals**'

5.2.7 Joystick → Press

5.2.8 pb MENU → Press

5.3 sw FULL AUTO → ON

5.4 sw FOCUS → A

5.5 sw IRIS → A

NODE2 Cam 1 & NODE2 Cam 2

5.6 sw POWER (two) → OFF

6. DATA DOWNLINK

   6.1 Using Imagery Transfer Tool, transfer videos to Videos for Downlink, select 'For POIC', include S/N (B/C) and input Plant Water Management into 'Input Brief Folder Description'.

   6.2 Notify **POIC** S/N or B/C 256GB SD Card (two) used, retain until downlink confirmed on the ground.

7. Return deployed Photo/TV equipment.

8. Stow equipment per Stowage Note.

Ground should update IMS for the following parts:
Plant Water Management 6 P/N PWM5601-02 TO: trashed (step 4.10)
Pump P/N CSELS_2310 TO: stow (step 8)
Power Cable P/N CSELS_2310 TO: stow (step 8)
Multi-Use Bracket TO: stow (step 8)
Inverter GFCI Cable 3' TO: stow (step 8)
Laptop Desk TO: stow (step 8)
LED Work Light (two) TO: stow (step 8)
Plant Water Management Root Type 3 TO: trash (step 4.10)
Flexible Bracket (two) TO: stow (step 8)
256GB SD Card (two) TO: stow (step 8)
Work Light USB Power Cable P/N WORKLIGHTCABLE-001 (two) TO: stow (step 8)

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
PWM5_6-UHR-01	Hazardous Materials	CZ1/3	Go to step 2.7, step 2.8, step 3.7, step 3.8 and step 4.10
OCAD 102398	Electrical	OCAD 102398	Go to step 4.1
STD-PWM-01	Hazardous Materials	CTL-6/6.2	Go to step 2.8, step 3.8, and step 4.10
STD-PWM-01	Flammability	CTL-4/4.1	Go to step 8
STD-CSELS-KIT2-01	Flammability	CTL-2/2.2	Go to step 8
AX-SNOW-UHR-1	Electrical	CZ1/2	Go to step 4.1
UNQ-CSELS-KIT2-02	Electrical	CZ2/3	Go to step 4.1

2.035 PLANT WATER MANAGEMENT 5&6 OVERNIGHT SAFING

OBJECTIVE:

To prepare hardware for overnight safing in between days of operation.

1. ✓All valves are closed
2. ✓Pump head tubing removed from pump head

NODE2 Cam 2

3. Stop recording to 256GB SD Card (two) on second NODE2 Camcorder with close-up view of MWA.
4. AUDIO RECONFIGURATION
   - 4.1 pb MENU → Press
   - 4.2 Joystick → '  **Audio Setup**'
   - 4.3 Joystick → Press
   - 4.4 Joystick → '**Select CH1/CH2 Input**'
   - 4.5 Joystick → Press
   - 4.6 Joystick → '**Input Terminals**'
   - 4.7 Joystick → Press
   - 4.8 pb MENU → Press
5. sw 120 VDC to 120 VAC Inverter SW2 → OFF (S/N 1038)
6. sw LED Work Light (two) → OFF
7. Place 2.0 CTB over Plant Water Management hardware on MWA and secure with Bungee.

   ✓All hardware covered

NODE2 Cam 1 & NODE2 Cam 2

8. sw POWER (two) → OFF
9. Using Imagery Transfer Tool, transfer videos to Videos for Downlink, select 'For POIC', include card S/N (B/C) and input Plant Water Management into 'Input Brief Folder Description'.
10. Notify **POIC** S/N or B/C 256GB SD Card (two) used, retain until downlink confirmed on the ground.
11. Stow per Stowage Note.

Table 1. Procedure Hazard Control List

Hazard Report Number	Hazard Title	Hazard Cause (CZ) #/ Hazard Control (CTL) #	Procedure Step(s)
STD-PWM-01	Flammability	CTL-4/4.1	Go to step 7
STD-CSELS-KIT2-01	Flammability	CTL-2/2.2	Go to step 7