

Passive Water Assurance Delivery System Final Report

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NASA Water Assurance Project

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Dr. Gioia Massa,

Attached is the team's report for the NASA Vegetable Production System (VEGGIE) for use aboard the International Space Station. Within the report you can expect to find project background information, design description and evaluation, and ultimately our conclusions and recommendations for the project. Cost Analysis, Design Risks, Outreach and Engagement efforts, and Further Considerations are also included for your convenience. From the information collected throughout the course of the project the conclusions were formed:

- Water can be passively delivered using a single capillary interface system.
- Harvestable plants were successfully grown from seed to harvest in the proposed single capillary interface system.
- Corded Nomex had the great capillary performance of all candidate materials and fits NASA's material flight requirements.
- Using the proposed system, crew time is reduced substantially with plants needing to be watered once every 45 days.
- The sponge propellant management device water reservoir design works theoretically under microgravity conditions and is based off of designs that are currently operational and functioning in microgravity conditions.

We would like to thank you for your continued support and guidance on the project thus far. We would also like to give special acknowledgement to Dr. Peter Ling, Dr. Gonul Kaletunc, Bizhen Hu, John McQuillen, and ORBITEC for their courteous donations of time and resources helping make this project a success.

Sincerely,

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Executive Summary

This report provides an analysis and evaluation of proposed design improvements to the internal water delivery system of NASA's passive vegetable growing system. The VEGGIE system is designed to provide fresh vegetables and psychological benefits for astronauts aboard the International Space Station. Preliminary testing conducted by NASA for the VEGGIE system revealed flaws in the water delivery system. In these tests, the interface between the plants and the water reservoir failed to provide passive water delivery through the system both in microgravity experiments and experiments conducted on Earth. Our team's goal was to fix this interface such that water can be passively delivered from the water reservoir to the plant rooting pillows to grow vegetative crops from seed to harvest. The system requirements outlined by NASA include: minimal total mass, on-demand passive water delivery, same dimensions as existing fixtures, minimal pressure on system to prevent leaking, zero mold growth, minimal swelling or clogging for non-flammable capillary materials, pressure stabilization between the water reservoir and plant pillow bags, even dispersal of water during initial priming, minimal bubble obstruction of capillary interface, maximum gas availability to plant roots, growth in a mixed artificial media (50:50 Arcillite:Fafard #2), and to avoid overwatering and drought conditions for plants.

The major proposed design improvements are to use a single-interface capillary cord design to directly connect the water reservoir to the plant-rooting pillows, and to alter the water reservoir to model a propellant management device (PMD) in order to ensure consistent and long term watering for the VEGGIE system. The plant rooting pillow required minimal changes outside of replacing the capillary mat on the bottom of the pillow with O-ring insertion points the single-interface capillary system.

Research was conducted to determine which materials are able to uptake water through capillary action to grow Outredgeous Lettuce plants from seed to harvest. The primary requirements to be met by the team's design and evaluation of the capillary interface were: continuous passive watering for 90 days using non-flammable capillary materials and a peak water delivery rate of 30 mL/hr./0.15 m². The results of the team's experimentation showed that the capillary material Nomex displayed the highest capillary water delivery potential with a maximum flow rate of 3.6 mL/hr. The Nomex capillary systems were the only capillary material to consistently grow Outredgeous Lettuce plants from seed to harvest, and displayed the highest average flow rate for multiple experiment sets. The Nomex

material was previously incorporated into the VEGGIE system using a matted version of the capillary material, though the team recommends using a cord configuration in the single-interface capillary system for greater system stability. Nomex has proven to be a promising material, as it has passed both health and fire standards for use aboard the International Space Station.

PMDs are made of materials that utilize surface tension and adhesive forces to overcome adverse accelerations to improve stability and ensure fluid delivery. PMDs are typically used in fuel tanks to ensure fuel delivery. The team recommends using a sponge PMD in order to mitigate bubble obstruction, decrease system weight, and ensure reliable water delivery to the capillary interface. The PMD water reservoir requires a rigid water reservoir and a vent tube for pressure stabilization. Since PMD's cannot be tested in 1-G (Earth conditions), further theoretical modeling and testing is required for the proposed water reservoir design.

The intent of this proposed system is to passively water plants in microgravity, though the technology is not limited to microgravity applications. The testing at The Ohio State University has proven that the design is highly effective on Earth, demonstrating that it could serve as a simple water delivery system in home and office applications. This would make vegetative crops more accessible in all indoor applications, thereby improving indoor air quality and occupant comfort. Additionally, this technology has great potential to be utilized in greenhouse plant production, cutting back on more sophisticated watering system energy and time requirements.

Introduction

The charge for scientific innovation, discovery, and exploration in outer space has long been led by the National Aeronautics and Space Administration (NASA). NASA is a United States government agency that created the civilian space program and conducts aeronautics and aerospace research. After becoming fully operational in 1958, most of the United States space exploration efforts have been led by NASA. One such project is the growth and harvest of vegetables in microgravity environments. At present time, astronauts consume food that is provided in packages with limited quantity and subpar quality. A team working at NASA and ORBITEC Inc. has developed the Vegetable Production System (VEGGIE) to address food supply issues with astronauts living in space for extended periods of time. Specifically, VEGGIE works to address these problems through the creation of a passive water delivery system as a way to grow fresh food aboard the spacecraft (Massa et al. 2013). The VEGGIE system (Figure 1, below) is composed of the physical plant, plant-rooting pillows, a capillary interface, and a water reservoir. VEGGIE was initially tested aboard the International Space Station and at the Kennedy Space Center. Both systems failed to consistently deliver water to the plants after two weeks and needed to be manually watered. The problem was isolated to the interface between the water reservoir and the plant-rooting pillow.

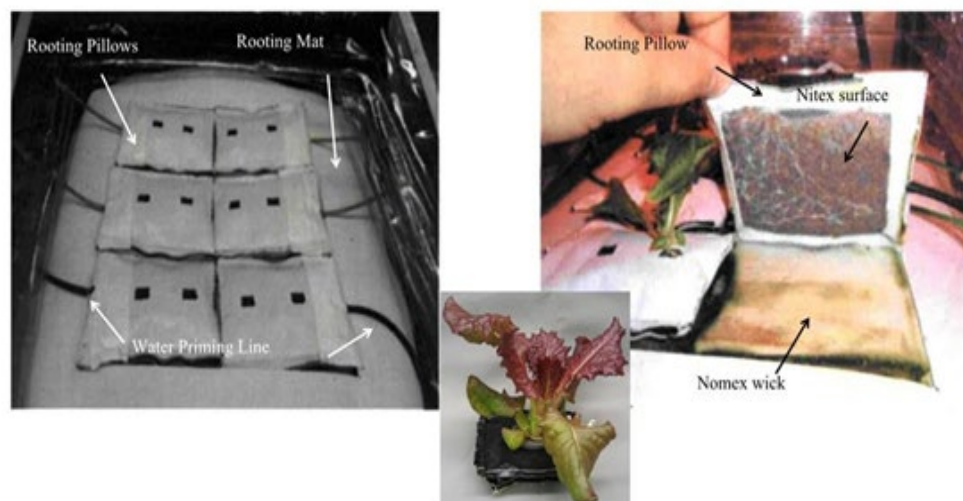


Figure 1: Rooting pillows and rooting mat of the system (left), Outredgeous Lettuce in plant pillow (middle), display of two interfaces to supply capillary action to the plant rooting pillow from the water reservoir (right).

The problems that occurred with VEGGIE are believed to be a result of: failed water delivery through capillary action, failed pressure equalization in the water reservoir, gas bubble obstruction of the capillary interface, or failed oxygen delivery to the plant root zone. The current system utilizes capillary action between the rooting pillow and the water reservoir to transport water from the water reservoir to the plant rooting pillows. The original VEGGIE system failure was not present until two weeks after the initiation of the priming of the system. The failure was noticed due to the plants starting to exhibit drought symptoms, indicating that water was unable to be supplied via capillary action from the water reservoir with the existing two-layered capillary interface. To mediate this issue, in microgravity the astronauts had to hand water the pillows to keep the plants growing until they could be harvested for consumption. This process of hand watering was time intensive for the astronauts, which was a huge drawback to the system. In an attempt to isolate where the issue in the system was arising, the test was re-ran at the Kennedy Space Center in Orlando, Florida. In the duplicate test at the Kennedy Space Center (a 1-G environment), the same issue with drought symptoms occurred after two weeks, indicating that the failure was not due to microgravity, and therefore could be isolated to failing capillaries.

The project sponsor, NASA, requests that the team be able to reduce crew time spent on watering the plants by first ensuring water delivery from the water reservoir to the plant pillows by identifying and removing conflicting interferences in the water reservoir. The requirements identified by NASA prior to February 2016 include: continuous and on-demand passive watering for 90 days using non-flammable capillary materials, a peak water delivery rate of 30 mL/hr./0.15 m², minimal system mass, zero mold growth, and the system must fit the present external dimensions of 35 cm x 21 cm. After a series of successes in experimentation at Ohio State University using the proposed single-interface capillary system, the team's scope was expanded by NASA to fit the following requirements: avoid vacuum formation in the water reservoir, even dispersal of water during priming, avoid bubble obstruction at the entrance to the capillary interface, and to ensure gas availability to the root zone in the plant pillow.

Background

Humanity's ability to explore deep space is directly linked to having a sustainable and reliable source of food and a healthy indoor air quality aboard each spacecraft. Having fresh food is vital for the health and well-being of astronauts during long space missions, and a healthy indoor air quality is a necessity for all living occupants. Not only do plants provide nutritional benefits, plant growth involves uptake of carbon dioxide and expulsion of oxygen, thereby providing a sustainable air system for occupants of the spacecraft (Fleming, *et al* 2012). There are several constraints with food production aboard each spacecraft: the microgravity environment, lack of light sources, pressure, and no natural source of water. Team members at NASA have developed a way to mitigate and work with these constraints using VEGGIE. The VEGGIE system has the ability to deliver water with zero energy input (not including the lighting fixtures provided to allow the plants to undergo photosynthesis) using capillary action (Subbiah 2013). However, after a two-week period of time, the capillary action of the wicking material is unable to meet the water demands of the plant (Fleming, *et al* 2012). Nomex, a fabric material composed of short nylon based fibers (in this system matted Nomex), is being used for capillary action. Although Nomex has proven promising for its wicking capabilities, it is not ideal for retaining water (Subbiah 2013).

The VEGGIE system is made of three primary components: the rooting pillow, the capillary interface, and the water reservoir. The system uses a media mixture (1:1 ratio) in the plant rooting bag of artificial soil (arcillite, there to provide pore space and reduce microbial growth since it is not organic matter) and a peat moss soil (Fafard #2). The passive water delivery involves passing water through a capillary material interface from the water reservoir into the plant-rooting pillows, which contain this growth media for the plants. The rooting pillow is where the individual plant will grow and be watered through capillary action until the plant is harvested for consumption (around 58-62 days of growing for Outredgeous Lettuce). Priming tubes are used in the initial processes to prime the rooting pillows for the vegetable seedling so that it has a moist environment to grow in and a connective flow can be established for capillary action from the reservoir to the plant-rooting pillow. The water reservoir is manually filled by an astronaut, and is the source of water supply for the VEGGIE system.

The failure of the original VEGGIE system was isolated by the Ohio State University team to the capillary interface between the water reservoir and rooting pillow

components. The issue between the water reservoir and the rooting pillow is a direct result of the capillary action failure, believed to be caused by swelling of the capillaries and/or failure to connect the short length fibers in the two-interface capillary matted system.

The NASA team has made attempts at several different methods to mitigate the issue, but none have been wholly successful at solving the problem completely. One major concern involving the existing capillary system is that air bubbles may be present within the capillary interface and are breaking the surface tension that is required for capillary action to be successful. In the original system, the water was being introduced to the reservoir by filling it up using a 25-milliliter syringe, which was potentially introducing bubbles into the reservoir (Subbiah 2013). However, results from this test have shown that the syringe had no effect of introducing bubbles to the system, and was not the main cause of failure. Follow up studies have found that the wicking capacity of Nomex varied during the course of crop growth, and dropped over a certain period of time causing drought conditions and ultimately the plant's death. This inconsistency of the wicking capacity is also stated in a support letter of the project provided by Dr. Raymond Wheeler of the Kennedy Space Center, "...several challenges with the approach, including loss of capillary connection between the reservoir and the root containment packets [pillows], change in pressure of the reservoir as the volume changed, and possible limitations to the wicking material."

After further discussions with NASA and results from the second VEGGIE system became available, a rising concern with the water reservoir was the bubbles that are found in the system. In microgravity water and oxygen do not mix together like they would on Earth. In microgravity water encases the oxygen bubble, forming a thin film around it due to water's adhesive property. These bubbles when present in the VEGGIE system completely block the flow of the water in the capillaries. This problem causes the roots to be either deprived of oxygen and/or water, causing failure of the system.

Detailed Design Description

The initial scope of the project was to solve the issue of water delivery contained within the interface between the water reservoir and the plant-rooting pillow. All designs and testing (see Design Evaluation) prior to mid-February 2016 were simulated and created to test materials to be used in the proposed single-interface capillary system. In late-February 2016, following a successful demonstration in early experimentation of the proposed single-interface capillary system, the project sponsor NASA reached out to the team to expand the scope to include a redesigning of the water reservoir and plant-rooting pillow.

Interface between the Water Reservoir and Plant-Rooting Pillow

Previous conceptual ideas proposed by the team were all based on the general idea of passive water delivery to the plant pillows via the water reservoir using capillary action. The final options considered are shown below in Figure 2 and Figure 3.

The design option shown in Figure 2 features a rigid multidimensional capillary design, which is also focused on addressing the roots' needs. It would do so by placing larger capillary capacity tubes at a lower height in the fixture such that the structure could be lowered once the plant matures, thereby allowing for a greater amount of water uptake by the plants. The pillows would be raised or lowered using a simple knob mechanism. The advantage of this system is that it provides water delivery on-demand to the plant pillows. The disadvantages to this design is that the system weight would be dramatically increased, the mechanism for raising or lowering the plants would increase the complexity of the system, and the height of the entire system may increase beyond the required dimensions outlined by NASA.

The design option shown in Figure 3 features another rigid capillary tube design. It is similar to the design option 2 shown in Figure 2, but without the larger capillary casing tubes at a lower height. Since the system is far simpler, lighter in weight, and it fits the existing dimensions of VEGGIE, the team decided to investigate this conceptual design.

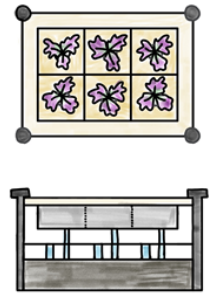


Figure 2: Top and side view of the selected conceptual VEGGIE design.

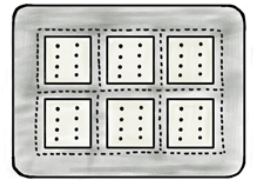


Figure 3: Top, side, and orthographic views of one of the considered conceptual VEGGIE designs. This design was not selected.

Originally the design was intended to use micro-polymer based rigid capillary tubes fitted within a larger casing tube bridge between the water reservoir and plant-rooting pillow. Capillary tubes were donated by Paradigm and consisted of materials including PETG, ETFE, polyethylene, and acrylic polymer on the scale of $187\mu\text{m}$ - $1000\mu\text{m}$ internal diameter. These tubes were then used in testing at The Ohio State University. The team immediately ran into problems involving the micro-polymer based rigid capillary tube's inability to stay primed for testing in ground conditions as well as the low strength of the polymer materials, which led to many test failures from the start. The reason the tubes wouldn't stay primed is likely due to the fact that gravitational forces on Earth are too strong to allow for the capillary rise required to bridge the gap from the water reservoir into the plant pillow bags (~ 2.5 in. or 6.35 cm). There was a tradeoff in achieving this height: as the diameter became smaller a greater rise in the height of the tube was possible, but the friction provided by the adhesive forces also grew per unit volume of fluid, thereby slowing the flow rate through the system and increasing the necessary plant suction forces to uptake available water.

Considering the constraints of a micro-polymer capillary tube system, the team decided to

look to alternative capillary materials to bridge the single-interface capillary system (shown in Figure 3).

To replace the micro-polymer based rigid capillary tubes, durable capillary fabric materials were used. The capillary fabrics were to be inserted within casing tubes (as shown in Figure 5) that bridge the gap between the water reservoir and the plant pillow bags (as shown in Figure 4). The casing tubes function to keep the fabric cords from drying out, control where evapotranspiration was occurring, and to keep the materials clean (see Figure 5). These casing tubes also allows for easier insertion points to the plant pillow and water reservoir system (fixed diameter size of the casing tube) for the single-interface system design. The casing tube shown in Figure 5 is to be permanently attached to a propellant management device within the water reservoir without an extension of the diameter on that end of the casing tube (see Figure 7 for AutoCAD model). The casing tube should be directly connected to the PMD upon manufacturing. The casing tube must also be porous on the water reservoir end in order to effectively give a path from the PMD bulk liquid to the capillary fiber within the casing tube.

On the plant pillow end of the casing tube, there will be a non-permanent connection piece for the plant pillow inserts, which will extend the diameter similar to both of the ends shown in Figure 6. The bottom of the plant pillow bag was designed with insertion O-ring structures for secure connection to the casing tubes. It is recommended that the casing tube is made of a NASA approved lightweight polymer to minimize the overall system mass and to ensure NASA safety requirements are met.

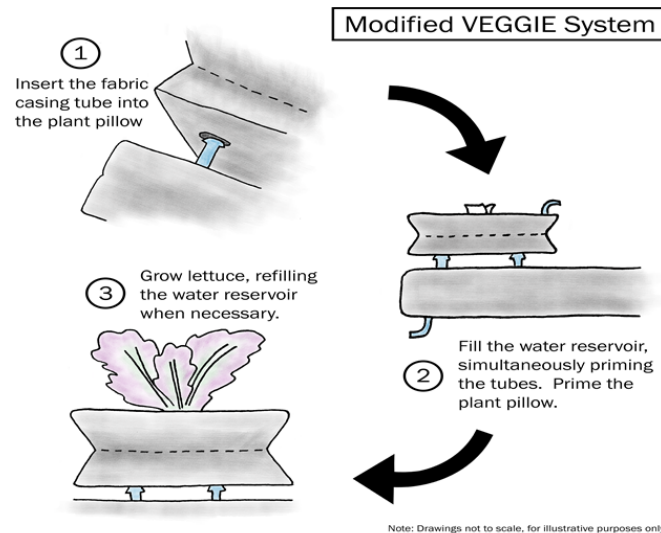


Figure 4: The concept of operations for the modified interface and how it would fit into the VEGGIE system as a whole.

There was a total of thirteen fabric types tested in order to determine the best capillary material to be used within the casing tubes for the final system. The tested capillary fabrics consisted of materials blends of: nylon parachute cord (325 and 550), hemp fibers, acrylic, wool, silk, viscose, Nomex, Kevlar, HMT, and commercial available capillary mat. The fabric chosen to be within the casing tubes is three stranded Nomex due to its' high water delivery rates (mL/hour, see Design Evaluation and Results) as well as its flame retardant properties. The Nomex capillary fiber is to be encased by the casing tubes and attached to the outside of each end of the casing tube using slits in the plastic. In the testing of the fibers at Ohio State University, this proved to be an effective method to keep the fiber secure during insertion into the plant pillows. This also allows the fiber to get as deep into the plant pillows as possible, which further ensures capillary connection between the water reservoir and plant pillow.

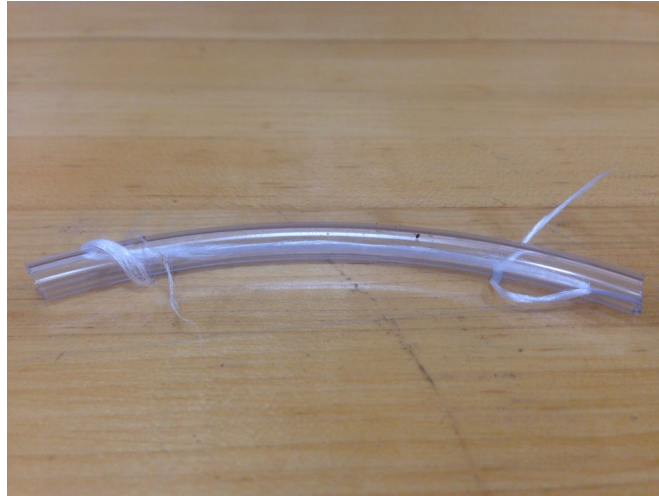


Figure 5: Casing tube with three strands of Nomex fiber fixed to each end of the 0.25 cm diameter casing tube.



Figure 6: Example casing tubes for the capillary interface (www.aliexpress.com).

As seen in Figure 7, the casing tube design will result in a 1-2 cm crop headspace loss due to the O-ring insertion method for connecting the water reservoir to the plant pillow using casing tubes. One design considered for the attachment of the system is having the casing tube be less rigid and to include inserts on the side of the plant pillows to mitigate this crop headspace loss. Placement of the casing tubes will be considered by the 2016-2017 NASA X-HAB Challenge team at The Ohio State University.

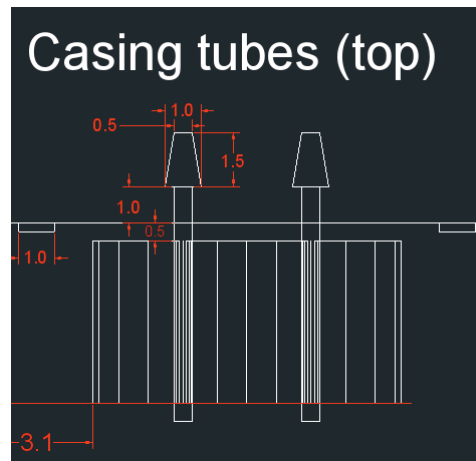


Figure 7: Casing tube connection to sponge PMD with dimensions (cm).

Propellant Management Device Water Reservoir Design

The water reservoir final design is created based off of sponge propellant management device (PMD), which are currently used on space crafts to ensure fuel delivery in microgravity. After extensive research into PMD designs the team narrowed down the candidate PMD structures to be used in the proposed water reservoir to either a vane, sponge, or hybrid PMD type. A vane PMD structure would connect the casing tube directly to the wall of the reservoir to communicate liquid from the likely liquid pool area to the casing tubes. A sponge PMD structure consist of panels in close proximity connected to the casing tube to ensure water stability over the capillary material through the porous casing tube that runs the length of the fins. A hybrid PMD structure would be a PMD type that is both connected to the reservoir wall and has a sponge PMD structure at each casing tube exit. After considering the advantages and disadvantages of each structure, the team came to the conclusion that the sponge PMD design would best suit the proposed water reservoir design.

It is recommended that the final sponge PMD structure be built of the same material as the casing tube (a polymer) so that they can be connected directly during manufacturing. PMDs are typically made of Titanium or Aluminum, and from the team's research there has never been a PMD designed with a lightweight polymer material. One other option is to use the matted Nomex material as a sponge PMD, which would decrease the overall system mass and theoretically should function similar to a rigid sponge PMD. More discussion about the material selection is included in Design Evaluation and Design Risk section

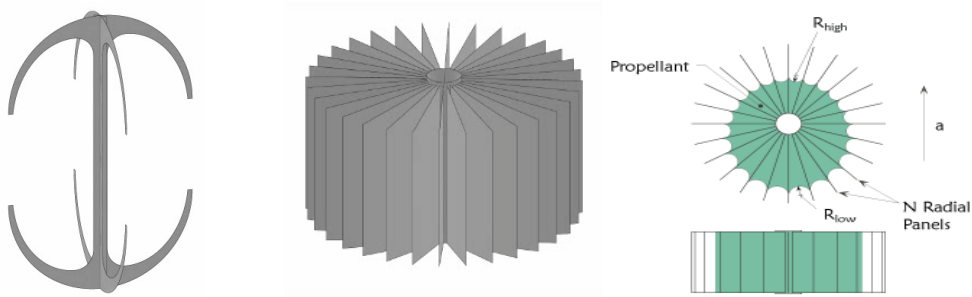


Figure 8: Left- vane design; middle- sponge design; right- sponge design during acceleration.

The sponge PMD design ensures water delivery based on predictable locations of the gas and liquid within the water reservoir based on shape, volume, effective gravity (which in this case is going to be low), and the surface tension of the liquid. The structure creates a continuous flow path from the bulk liquid to the outlet port of the reservoir. In microgravity, based on theory, water is attracted to corners since capillary forces dominate over gravitational forces. Since the contact angle is nearly zero for a water/Nomex interface, the team expects the water will be constantly retained within the PMD structure, even in the case of adverse accelerations or recovery maneuvers of the space-craft (as seen in Figure 8 - right picture).

Gas is a known inhibitor of capillary action, as it breaks the water's cohesive connection between the water reservoir and the plant pillow, thereby inhibiting capillary action. By using the corners made through the use of PMDs in the water reservoir, the water adheres itself to corners, and will be drawn upon by the roots when needed, while keeping the bubbles away from the capillaries and the roots. By keeping gas out of the single-interface capillary system, continuous on demand water flow will be possible for the duration of plant growth. This system design (shown in Figure 9 and Figure 10) theoretically keeps the gases restrained to the bottom of the reservoir and the water restrained at the top, so the system would be a rigid reservoir (instead of flexible like the current system is) with the bottom containing a venting tube to relieve any pressure or vacuum formation.

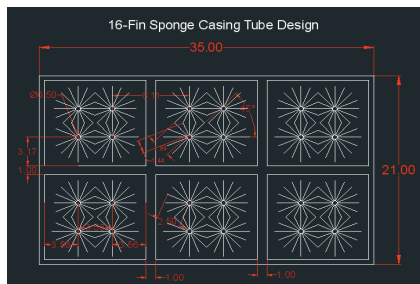


Figure 10: Top view of the 24 casing tube configuration PMD design with dimensions (cm).

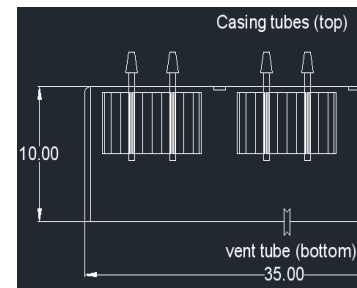


Figure 9: Front view of the rigid water reservoir design with dimensions (cm).

The proposed sponge PMD water reservoir design will reduce crop headspace by 5 cm. This comes as a result of doubling the reservoirs height from 5 cm to 10 cm to effectively incorporate the PMD structure to the casing tube design. Alternative designs aimed to mitigate this crop headspace reduction will be considered by the 2016-2017 NASA X-HAB Challenge team at The Ohio State University. More information related to this issue is included in the Design Evaluation and Design Risks sections.

Using a vent tube, the rigid water reservoir will allow for airflow and pressure balance within the entire system of VEGGIE, a major concern in the current system. The vent tube will be placed on the opposite side of the water reservoir to the plant-rooting pillow connections to allow for system pressure balancing and effective initial priming. PMD designs typically include a vent tube in order to mitigate the same concern. During priming, this vent tube must be covered by a towel to prevent excessive water leakage into the cabin space. More information related to the vent tube is included in the Design Evaluation section.

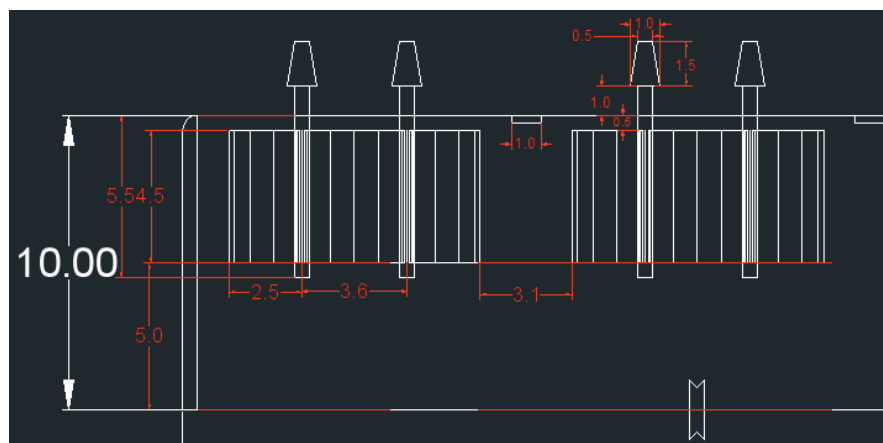


Figure 11: Front view of water reservoir with PMD and casing tube dimensions (cm).

between the media and the water should keep the media contained within the plant-rooting pillow following system priming.

Another solution to increasing oxygen access to the plant root zone is to increase the porosity for the allowance of more gases in the root zone. This could be achieved hexagonal, honeycomb-like structures to the media mix to increase air pore space, allowing for longer oxygen availability to the root-zone of the plant pillow systems. Each of these ideas will require research and development prior to their implementation.

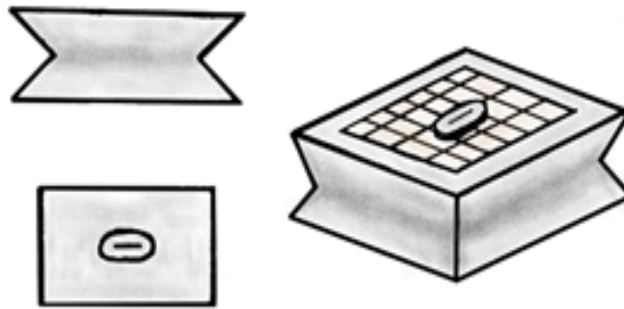


Figure 13: The new design plant-rooting pillow, the orthographic view showing it open to the environment.

Concept of Operations - Proposed System Assembly

The system is assembled by directly connecting the water reservoir to the plant pillows using the casing tubes. Below is a concept of operations for assembling the system aboard the ISS. See figure 4 for visual aid.

Materials required:

- Plant Rooting Pillow(s)
 - 1-6 plant pillows depending on crop and plant rooting pillow sizing
- Water ~ 6-8 Liters
 - Dependent on final water reservoir sizing
 - Proposed design is 10 x 35 x 21 cm, or ~ 7.35L
- Water Reservoir
- Towel
- Vent Tube Clamp (any tube clamp should suffice)

Assembly Instructions:

1. Take all plant pillow bags and insert the casing tubes protruding out of the water reservoir into their corresponding O-rings located on the bottom of the plant pillow bag.
2. Repeat Step 1 for all plant rooting pillows being added to the system.
3. Check to ensure all casing tubes are effectively inserted into their respective plant pillow system.
4. Place a towel over the vent tube located on the bottom of the water reservoir.
5. Begin priming the system from the water reservoir using the existing priming tubes.
 - a. Be careful not to insert water into the reservoir too quickly, as this could result in plant media escaping from the plant pillow bag into the cabin space.
6. Once the water reservoir is filled, check to see if water is contained within the casing tubes.
 - a. If water is present, the capillary fibers have been effectively primed.
7. If needed, begin adding water to the plant media pillow.
 - a. This step is only required if sufficient water did not go through the casing tube into the plant pillow.
 - b. Be careful not to insert water into the plant media pillow too quickly, as this could result in plant media being dislodged into the casing tube or water reservoir.
8. Check for bubbles in the casing tubes.

9. (if necessary) If bubbles are present in the casing tubes, clamp the vent tube shut, effectively closing the water reservoir system. Begin adding water until pressure causes the bubble in the casing tube to be dislodged into the plant pillow.
10. (if necessary) Close all water insert tubes and release clamp on vent tube.
11. Collect any water that has escaped the system using vent tube towel.

Design Evaluation

Selection of Single-Interface Overall Design

The single-interface overall system design was chosen among four designs using a Pugh's Design Matrix (Appendix A: Pugh's Design Matrix of Initial Designs for Capillary Interface) that evaluated the key criterion/requirements that were provided by the sponsor. A weight was then placed on each requirement signifying their level of importance. The four designs (Design 3 is representative of Figure 3, the chosen design) were weighted against one another to aide in the decision of which interface was to be used.

Selection and Testing of Capillary Materials

Theoretical Testing

To theoretically test the flowrates of the capillary tubes, software provided by Pacific Northwest National Laboratory, operated by Battelle, was used. The software models capillary action using the equations located in Appendix B: Theoretical Calculations to Test Flowrates of Capillary Tubes. The model inputs included were back pressure, column length, column inner diameter, and the solvent viscosity of water. The output was the volumetric flow rate which was based on the linear velocity through the capillary system. All calculations are performed without the influence of gravity.

Polymer flow rates were modeled using a back pressure between 0-1 bar, based on the water suction forces typical of plants. The results indicated that the flow would be achieved in microgravity with much more than 30 mL/hr provided using a column diameter greater than 225 μ m, under operating conditions greater than 0.1 bar or 10 kPa (shown in Table 1). These theoretical calculations are important not only in the initial proposed rigid polymer capillary tube system modeling, but also in understanding the influence of porosity in a non-uniform fabric capillary system.

Using the same equations described above, it is seen that linear velocity is exponentially related to the radius. This means that with an increasing "effective" radius in our system, we should expect to see a greater linear velocity in our system (assuming the same root pressure), thus giving a great volumetric flow rate potential through the capillary fibers. It should be noted that determining the systems effective radius is nearly impossible since the fabrics are non-uniform and since the material changes shape following accelerations and other external forces. The only way the effective

radius could be measured is to determine the average flow rate through a specific fiber with the system inputs known, and then to calculate backward to determine the “effective” radius (see Appendix B for equations). When the team speaks of the effective radius, we are discussing its theoretical importance rather than an absolute variable to be determined.

Since the fabric system is considered a non-uniform capillary system, the team looked to soil science for a better understanding of capillary stability. Simply put, capillary stability is how well the system will be able to remain primed following the initial wetting of the fibers. In soil science, capillary forces and capillary stability increase with decreasing particle size, or increasing surface area per unit volume. This is apparent in clay soils which retain water very well due to their smaller particle size, resulting in an environment where root pressure must be much greater for plants to obtain water from the soil. In our system, this is analogous to having smaller spaces between the fibers (smaller effective radius), thus increasing capillary forces per unit volume (similar to smaller rigid tubes for the equations given in **Appendix B: Theoretical Calculations to Test Flowrates of Capillary Tubes**). In our proposed system, this is important because drying of the fibers can disrupt the capillary flow and lead to system failure. Conversely, if the system is too stable (analogous to the clay example), or holds on to the water too “tight,” the plants may not have enough root pressure to move the water from the water reservoir to the plant-rooting pillows.

This leads us to two conclusions: (1) increased effective radius of our system will increase the volumetric flow rate potential of the system, and (2) decreased effective radius of our system will increase the systems capillary stability. Clearly these two variables are inversely related, and must be balanced to maximize the capillary fiber system performance.

Back Pressure	Column Length (inches)	Column Internal Diameter (μm)	Volumetric Flow Rate (mL/hr)
0.1	2.5	187	19.1181
0.1	2.5	190	20.3748
0.1	2.5	200	25.0149
0.1	2.5	225	40.06902
0.1	2.5	270	83.0871
0.1	2.5	288	107.55948
0.1	2.5	300	126.63792
0.1	2.5	375	309.17454
0.1	2.5	380	325.99662
0.1	2.5	1000	15634.30854

Table 1: Volumetric flow rates based on column internal diameter.

Long Term Durability Tests for Capillary Materials

After determining that the polymer capillary tubes would not fit the design requirements of the system due to priming concerns, the team began testing different capillary fabric materials. There were two main requirements that the capillary fabrics must display: continuous passive watering for 90 days and a peak water delivery rate of 30 mL/hr. The capillary fabric must also be reusable in multiple plant cycles, thus the fibers were chosen based on their durability over time. In order to determine which fabrics could match the delivery of 30 mL/hr while ensuring continuous flow for the 90-day requirement, the materials underwent long-term durability tests (LTDTs). The LTDTs



Figure 14: Each sample had three trials with the paper towels primed by the capillary cords in the containers

consisted of multiple fabric blends including: parachute cord (325 and 550), hemp fibers, acrylic, wool, silk, and viscose. These blends were all connected to a water reservoir and through the lid onto an evaporative surface (3" x 3" paper towel), as shown in Figure 14. Over time the evaporation of water from the paper towel pulls water out of the reservoir, and the amount of water that passes through the capillary interface is displayed as a change in mass of each system. Each fiber had 3 replicates.

The materials were chosen based off a list of common non-flammable fabrics. From the LTDTs, the daily and hourly flow rate was calculated for each sample. Towards the sixty day mark of testing, flow rate data was collected every three days. Environmental conditions were tracked throughout the entire experiment in order to determine the effect of humidity and temperature of the experiment space on the flow rate of the capillaries. Once plant reservoirs were built, air velocity of the environment surrounding the LTDT and the plant reservoirs was also recorded.

Plant-Pillow Experiments

In the Plant Pillow Experiments (PPE), a similar experiment was conducted but to test the capillaries with living plants in the artificial plant media. The plant pillow experimental set-up was based on the previous work done by Dr. Gioia Massa and her team in “Preliminary Species and Media Selection for the Veggie Space Hardware.” The type of pillow casing, media mixture, and dimensions were all determined from that paper. Notably, the team did not add the recommended fertilizer to the PPE experiments, which was thought to affect overall water uptake for each of the experiments, especially towards the end of the PPE. Since all of the fabrics were deemed flammable by the NASA team following the LTDTs, the team at Ohio State chose to pursue materials: Nomex, Kevlar, PETG (rigid micro-polymer tubes), ETFE (micro-polymer), and HMT due to their flame retardant capabilities. To compare these new materials with fabrics tested in the LTDTs, the highest performer (nylon parachute cord - 325) was included in PPE.

In the PPE, a total of 13 samples were prepared in the plant pillow experiments. Experimental sets were prepared in three sets: (1) the first set was prepared February 2, 2016 with the purpose of showing that the system can grow from seed to harvest, (2) the second set was prepared February 15, 2016 with the purpose of showing the maximum flow rates using larger electrostatic bags and larger transplanted lettuce plants, and (3) the third set was prepared February 26, 2016 with the purpose of further examining maximum flow rates with transplanted mature Outredgeous Lettuce plants using the candidate materials: Nomex, Kevlar, and rigid polymer tubing (ETFE), along with a control. At the same time, new lighting fixtures were put on the plants for a higher light intensity, which increased water uptake in all experiments. In the case that any plant died, mature plants were transplanted into the system that had failed and then re-primed with the death of the plant recorded. Each replant is recorded and shown on the total water uptake graphs (see Results). Daily water uptake by the plant was recorded by using the initial and final mass each of the experimental systems each day data was collected. The control for the PPEs consisted of Nomex cord with no lettuce plant and with a comparable opening at the top of the pillow to the pillows with plants included. The PPE systems were all kept in similar environmental conditions with randomized rotation of the plants under the lighting fixtures to prevent bias from placement in the testing area. Plant experiment #10 Technora was removed from the experimental set after its water reservoir broke and the plant died on day 25 for the set. Water was still available to the fiber prior to the water reservoir breaking, and plant death was not attributed to the reservoir breaking.

Additional Capillary Material Considerations

After discovering that all of the fibers tested in the LTDT tests would not pass fire-safety requirements for use aboard the ISS, the team determined Nomex, Kevlar, and HMT were the only candidate materials that may be used in the single-interface capillary system based on NASA requirements.

Nomex and Kevlar are isomers of one another. The only difference between their structures is that Kevlar has a para-aromatic structure, while Nomex has a meta-aromatic structure (see Figure 15). This slight difference effects their macroscopic structure, which effects the melting point, adhesive forces present with water, and the strength of each material. Kevlar has a melting point of 500°F while Nomex has a melting point of 350°F. Additionally, Kevlar has a greater tensile strength than Nomex, though both are very strong materials. The most notable difference for the team's proposed single-interface capillary system is the way each material interacts with water. Since Kevlar forms long parallel polymer layers, it only allows for water to form hydrogen bonds with single layers of the material. Nomex on the other hand forms more of a helical polymer structure, which creates narrow hollow polymer fibers. This shape exposes more molecules to water, increasing the number of hydrogen bonds possible for the structure. The greater the number of hydrogen bonds, the greater the adhesive forces between water and the material, resulting in a greater capillary potential. In fact, Nomex has been used as a semi-permeable membrane in desalination operations for this reason (*Nomex Characteristic and Production*). This could explain why the team noticed greater capillary stability and capillary flow in the Nomex fibers over the Kevlar systems in the PPE.

Hybrid Membrane Technology (HMT) was recommended by DuPont. HMT is typically used in nanofiber energy storage separators. It is made of a uniform nanofiber web made with nylon 6,6, similar to the Nylon 325 and 550 samples included in the LTDTs and PPEs. Nylon 6,6 is not an approved material for spaceflight, a notable disadvantage for the material. Additionally, the material has a porosity of 40%-90% with a pore size less than 1 μm , and a thickness of 20-70 μm , making it very fragile; another disadvantage to using the fiber. Despite the material performing well in PPE, the team does not recommend the material for the final VEGGIE system design due to these material considerations (Dupont *Hybrid Membrane Technology (HMT)*).

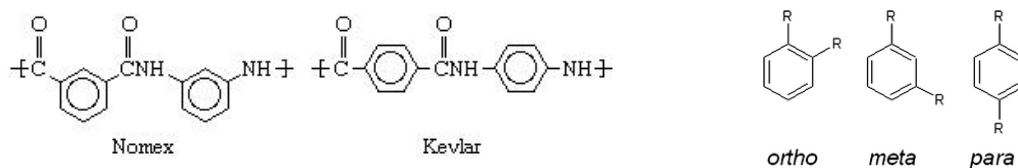


Figure 15: Left – Nomex and Kevlar chemical structures, right – aromatic ring bond types

source(s): <https://www.britannica.com/science/aramid> and <http://pubs.rsc.org/en/Content/ArticleHtml/2012/RA/c2ra01004f>

Selection of Sponge PMD Water Reservoir Design

The PMD water reservoir design was chosen because of the success of PMDs in over 500 microgravity flights with zero delivery failures (PMD Technology). Since PMDs come in a variety of configurations, the team first narrowed down our desired PMD type by analyzing designs that allow for refueling and for long term use of the system. This led the team to consider two main PMD types: vane and sponge PMD structures. These PMD types were then weighed based on their advantages and disadvantages of each system based on existing literature.

Vanes find their biggest advantage in the simplicity of their design. They are much lighter than the sponge design, cheaper to manufacture, and highly reliable for fuel delivery. Because of the open flow path, high rates of liquid passage through the outlet port can be achieved before gas ingestion occurs. Vane designs however cannot supply medium to high flow rates and cannot sustain liquid-only flow under medium to high adverse acceleration because of their weak capillary pumping forces in relation to sponges. Because of this, vanes should be implemented in systems that experience minimal accelerations and require low demand flow rates.

The major reasons a sponge design is preferred over a vane design is because of their strength. Sponges have the capacity to handle similar flow rates to vane designs, but can also be used to control the ullage (unfilled space in a container) and liquid contained in the water reservoir. This allows for greater bubble mitigation, a primary requirement for the water reservoir design. The disadvantages to the sponge design is the mass it adds to the overall system.

PMDs are not verifiable in ground tests because of fluid behavior in a 1-G versus microgravity environment which will not have the same attractive forces to corners. Most modeling is done using FLOW 3D. The team recommends NASA contact PMD experts to model any potential vane, sponge, or other PMD structures to be used in the final VEGGIE design.

Sizing of Sponge PMD

The required diameter for the sponge component of the PMD was determined using the 30 mL/hour specification for the capillary system. The sponge PMD must hold enough water to accomplish this flow rate for one orbit of the ISS around the Earth, which takes approximately 92 minutes, or approximately 1.5 hours.

$$Total\ Volume = 30 \frac{mL}{hr} \times 1.5\ hr = 45\ mL$$

Using these values, we see that the sponge PMD must have a volume of 45mL.

$$45\ mL \times 1 \frac{cm^3}{mL} = 45\ cm^3$$

Which is the equivalent of 45 cm³. Using this value, we determine the minimum diameter of the sponge PMD. In order to minimize the depth of the water reservoir and to save crop headspace, the depth (height) of the sponge component of the PMD was reduced to 4.5 cm. This also allows for the system to have room for the casing tube inserts.

$$45\ cm^3 = h \times \pi \times r^2$$

$$r = 1.78\ cm$$

Where h is the depth of the sponge, and r is the radius of the fins. Since the height is fixed to a maximum of 4.5 cm, this leads us to a fin radius of 1.78 cm to achieve the required 45 mL. John Mcquillen, a Senior Aerospace Engineer at NASA's John Glenn Research Center, recommended that we increase this size to 2.5 cm in order to achieve proper bubble mitigation. This also allows for the team to give room for the casing tube inserts (0.5 cm used, see Figure 11). Since the PMD fixture itself takes up some of the final volume, we increased the radius of the sponge PMD by approximately 140%, giving us a radius of 2.5 cm. Using this value, we assume a thickness of 0.25 cm per plate, and determine the volume decrease due to the plates.

$$Fin\ Volume = 0.25\ cm \times 4.5\ cm \times 5\ cm \times 8\ plates = 45\ cm^3$$

Finally, we see that the final design open flow area is:

$$Open\ Flow\ Volume = Total\ Volume - Fin\ Volume = h \times \pi \times r^2 - 45\ cm^3$$

$$\text{Open Flow Volume} = 43.36 \text{ cm}^3 = 43.36 \text{ mL}$$

The team believes this 43.36 mL value should be sufficient for accelerations experienced during one Earth orbit since the PMD structures are so small, and because each individual sponge PMD is connected to at least one other sponge PMD, further increasing the stability of the overall system. By connecting individual sponge PMD systems, the water should theoretically stay within each plant pillows' four PMDs during larger accelerations.

Number of Fins

Since water tends to corners in microgravity, the greater the number of fins, the greater the water retention capabilities of the system. However, with an increase in the number of fins per sponge PMD, there is also an increase in system weight, complexity of the system, and difficulty in manufacturing the individual PMDs. It was recommended by John Mcquillen, a Senior Aerospace Engineer at NASA's John Glenn Research Center, that the sponge PMD have at least 12 fins (6 plates) in order to effectively retain the water within the structure. In order to connect each sponge PMD to adjacent PMDs for greater system stability to each plant pillow, 16 fins were used. This gives an angle of 22.5° between each fin.

Sizing of Water Reservoir

The water reservoir overall size was dependent on the sponge PMD sizing. John Mcquillen, a Senior Aerospace Engineer at NASA's John Glenn Research Center, recommended that the height of the water reservoir be twice that of the fin height to allow for enough space for bubbles in the system to reside. This would lead to a total height of 9 cm, up from the current VEGGIE system's height of 5 cm. In the proposed water reservoir design there is a 0.5 cm gap between the "top" of the water reservoir (where the casing tubes are inserted) and the sponge PMD fins. This leads our design to have a total height of 10 cm, doubling the initial height of the water reservoir. This leads to a 5 cm crop headspace loss, a notable disadvantage to the system that is discussed in greater detail in Design Risks.

PMD Material Selection

One challenge with repurposing the PMD design into a water delivery system is determining which material would best fit the VEGGIE application. The Ohio State University team considers using one of the following materials for the fins on the sponge PMD structure: a polymer based sponge PMD, a matted Nomex sponge PMD, or a sponge PMD made of titanium or aluminum. Each of these materials were weighed based on their advantages and disadvantages with respect to the proposed VEGGIE system.

PMDs are typically made of aluminum or titanium for fuel delivery applications. The advantages of a metal based PMD is that it can withstand the high temperatures of fuel combustion, large fuel flow rates (liters/second), and the large forces that accompany the accelerations. With the VEGGIE, there is no concern for any of these requirements. The disadvantages of such a system would be the difficulty in finding the proper connection to the polymer based water reservoir, the increased final mass of the system, and that the structure could possibly puncture the water reservoir causing leakage of the system. For these reasons, the team does not recommend using a metal based sponge PMD structure.

The advantages of a rigid polymer based sponge PMD is that the material could be directly connected to the casing tube during manufacturing and polymers are lightweight. The disadvantage of a rigid polymer based system is that they are fragile and have never been tested in a PMD configuration. The advantages of using a Nomex based sponge PMD is that it is the lightest of the three candidate materials, it is porous which allows for water retention inside of the PMD structure and increases the total open flow volume capacity, and the material itself exhibits capillary action which may increase the overall system stability by allowing water to be “shared” between individual PMDs. The disadvantages of a matted Nomex based sponge PMD is: it would be difficult to adhere to the rigid polymer based casing tube, it is flexible- which means the angles between fins wouldn’t be fixed thus making system modeling difficult, and that the material also has never been tested in a PMD configuration.

After considering these advantages and disadvantages for each material, the team recommends using either a polymer or matted Nomex sponge PMD as they significantly decrease overall system mass along with the chances of a puncture in the water reservoir. Further research and development is required for this component of the water reservoir design.

Vent Tube

As water is wicked into the plant pillow, pressure is stabilized by air entering through the vent tube. The previous VEGGIE design incorporated a flexible bag to stabilize pressure, but since the system has failed the team believed that the flexible design could have been a contributor to the failure. All operating PMD devices require a vent tube for pressure stabilization, and is recommended for the team's final water reservoir PMD design for this reason.

Results

Long Term Durability Tests for Capillary Materials

From the Long Term Durability Tests (LTDTs), the nylon had the highest flow rate of water, though differences between LTDT samples were minimal. The LTDT data was mainly used to determine the effects of environmental conditions on the flow rate of the average flow rate of 12 samples used. As seen in Figure 25, there is an inverse relationship between the average flow rate (see Figure 16) and the humidity of the environment. This is to be expected, as evapotranspiration rates decrease in high humidity environments.

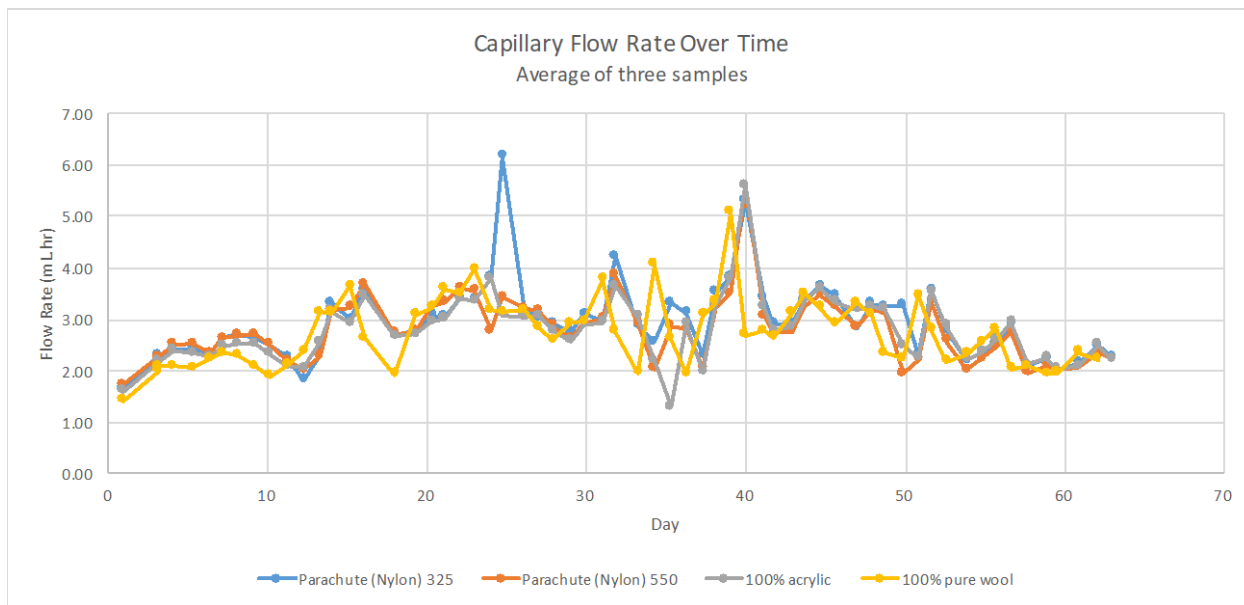


Figure 16: LTDT capillary flow rate over time, three replicates per material.

Capillary Material	Average
Parachute (Nylon) 325	3.29
Parachute (Nylon) 550	3.18
100% acrylic	3.25
100% pure wool	3.32

Table 2: Average of three samples for LTDT capillary materials.

Plant Production Experiments

In the PPE, there was an increase in every system's flow rate for all of the samples once lights fixtures were in place on day 25 for the first set (February 27, 2016). This is likely due to the increase in light levels from $25\text{-}50\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ to $300\text{-}500\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Experiment conditions were dependent on the environment allotted by The Ohio State University. Temperature and humidity were recorded at the same time of plant measurements to know the conditions for the plant system. The humidity values recorded to range from 30 - 80%. Air speed ranged from 0 m/s - 0.70 m/s, further effecting evapotranspiration rates. A correlation was observed between the average flow rates for 12 LTDT samples to the relative humidity (Appendix C: Environmental Considerations and Average Flow Rates, Figure 1). The major trend is the relative humidity is inversely proportional to the average flow rate, which is consistently seen in the PPE.

Each PPE experiment is evaluated with reference to other samples planted at the same time. This was done so to compare each set without environmental and biological discrepancies between experimental sets (such as growth cycles and differing environmental conditions for each day).

Capillary Experiments #1 - #5

The Nomex samples (#3 One Strand Nomex and #4 Three Strand Nomex) were the only experiments in the set to grow fully mature plants from seed to harvest. #1 Nylon Parachute cord, #2 Kevlar Cord, and #5 270 μm PETG all failed to grow plants from seed to harvest. In the case of plant death, transplants were planted in place of the dead plant. This allowed the team to continue testing the materials after re-priming the failed systems. For each replant, plant death is indicated on Figure 26. Notably, sample #4 Three Strand Nomex had a 43% higher flow rate than sample #3 One Strand Nomex, indicating the greater the number of capillary fibers, the greater the potential for higher flow rates to be achieved in the system. Further research into this concept will be required for the final design. See "Selection and Testing of Capillary Materials – Theoretical Testing" for more information regarding the effect of capillary size. See Figure 26 total water uptake over time and plant death information. In the figure plant death is indicated by an arrow with the corresponding plants color and the sample set is set back to zero water uptake. Average flow rate for the 100-day duration experiment is shown in Table 3. For visual reference a picture was taken on day 90 to show the plant health (see Figure 30). The health of each plant had declined, likely due to lack of nutrients due to the team not adding fertilizer to each plant pillow bag.

Capillary Experiment	Average Flow Rate (mL/hr)
#1 Nylon Parachute Cord	0.366
#2 Kevlar Cord	0.387
#3 One Strand Nomex	0.367
#4 Three Strand Nomex	0.525
#5 270 μ m PETG Tube	0.367

Table 3: Capillary Experiments #6 - #9

Capillary Experiments #6 - #9

Experiments #6 - #9 all included transplants, and were intended to display the highest flow rates possible for each of the fibers. They also had a volume of ~ 350 mL per plant pillow, allowing for greater root development. Three Strand Braided Nomex samples had the greatest capillary performance in the set. Multiple plant deaths were seen in the #7 Three Strand Braided Nomex sample. This was likely due to failed root establishment upon transplanting. The third transplant ended up having the greatest total water uptake, indicating it was not a failure in the capillary water delivery system. Hybrid Membrane Technology (HMT) provided by DuPont as a recommend material also performed well and was able to maintain capillary movement of water for the duration of the experiment. However, due to HMT's undesirable material characteristics (see introduction), HMT is not recommended for the final system. The #9 300 μ m PETG Tubes had the worst performance, with plant death around day 25. The plant remained in that system for the rest of the experimentation to serve as a reference for the growth of the three other plants that performed well. All experiments began flowering around day 80 of the experimentation, and can be seen in Figure 29.

Capillary Experiment	Average Flow Rate (mL/hr)
#6 HMT	0.503
#7 Three Strand Braided Nomex	0.621
#8 Three Strand Braided Nomex	0.586
#9 300 μ m PETG Tubes	0.337

Table 4: Capillary Experiments #11 - #14

Capillary Experiments #11 - #14 and Control

Experiments #11 - #14 all experienced plant stress immediately after being transplanted. The #13 Three Strand Braided Nomex sample initially had the greatest flowrate observed in the team's experimentation, but it sharply dropped with all of the samples around day 10 and remained low. It is thought that the experimental set had the following errors: environmental stresses, root

establishment, biological influence (algae and root growth into water reservoir), or air bubble blockage in the casing tubes.

Capillary Experiment	Average Flow Rate (mL/hr)
#11 Kevlar Cord	0.186
#12 Kevlar Cord	0.526
#13 Three Strand Braided nomex	0.495
#14 300 μ m ETFE Tube	0.350
Control	0.109

Table 5: Average flow rate for experiments #11 - #14 and control

Summary of Results

The results indicate that the Nomex is the most stable and capable capillary fiber of all tested materials. For this reason, it is recommended to be used in the proposed VEGGIE system design. The average flow rate over 100-days of experimentation is included in Table 6. Nomex samples had the greatest flow rates in both of the first and second sets of experiments, and a comparable flow rate to the #12 Kevlar experiment in experimental set three. Other than the plant death observed in experiment #13 Three Strand Nomex, all Nomex samples grew healthy mature plants. As discussed, the team believes experiment #13 died due to environmental stresses and not due to a failure of the capillary interface. The capillary materials and plant pillow from the #13 Three Strand Nomex experiment is now being recycled and used for a new set of experiments to further investigate this anomaly. No other materials were able to grow a healthy and mature Outredgeous Lettuce plant for the 90-day requirement.

Included in Figure 18 is a graph the average of three replicates of the “Three Strand Nomex” samples (#3, #4, and #13) compared to the growth curve provided by NASA from the previous VEGGIE tests done at Kennedy Space Center. Two lines are represented on the curve. The line labeled “Nomex” is the average of the three experiments, and the line labeled “Nomex x6” is that data multiplied by six to represent a complete VEGGIE system consisting of six plant pillows. This was done because it was untold whether the curve provided by NASA was one plant system, or an entire VEGGIE system with six plants. The NASA growth curve only included data for 60 days of growth. After the 60 days of growth the NASA experiments reached over 3 L of total water uptake for the experiments. The experiments at Ohio State University had only reached 770 mL of water uptake for one plant pillow (or 4.6 L for a system of six plants) after 60 days of growth. There is a decrease in water uptake following day 70, likely because the plants began flowering after being moved into a new lab pace. It was noted during a virtual presentation to Kennedy Space

Center that the plants grown at Ohio State University had an unusually low water uptake curve for the experimentation, indicating that the NASA growth curve was for only one plant. In which case, the team's experiments only had about $\frac{1}{3}$ the water uptake of the NASA growth experiments.

Capillary Experiment	Average Flow Rate (mL/hr)
#1 Nylon Parachute Cord	0.366
#2 Kevlar Cord	0.387
#3 One Strand Nomex	0.367
#4 Three Strand Nomex	0.525
#5 270 μ m PETG Tube	0.367
#6 HMT	0.503
#7 Three Strand Braided Nomex	0.621
#8 Three Strand Braided Nomex	0.586
#9 300 μ m PETG Tubes	0.337
#11 Kevlar Cord	0.186
#12 Kevlar Cord	0.526
#13 Three Strand Braided-nomex	0.495
#14 300 μ m ETFE Tube	0.350
Control	0.109

Table 6: Average flow rate over 100-day experimentation for all PPE experiments and control.

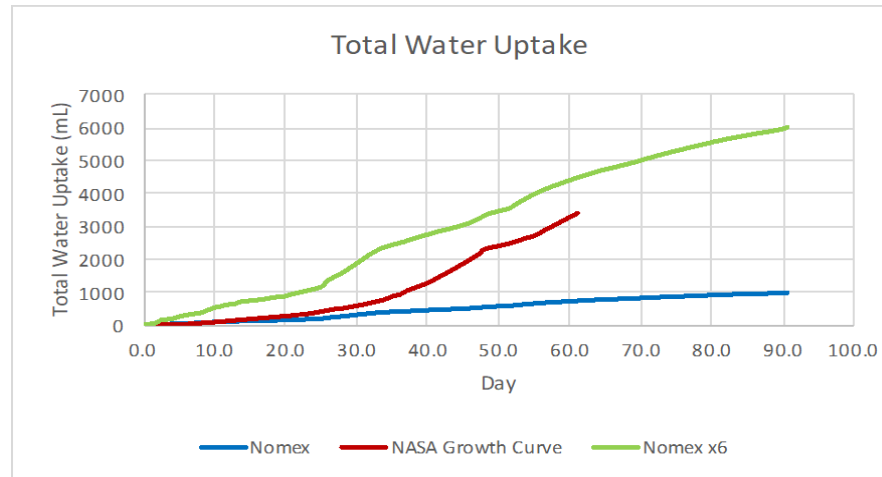


Figure 17: Nomex total water uptake over time compared to NASA growth curve.

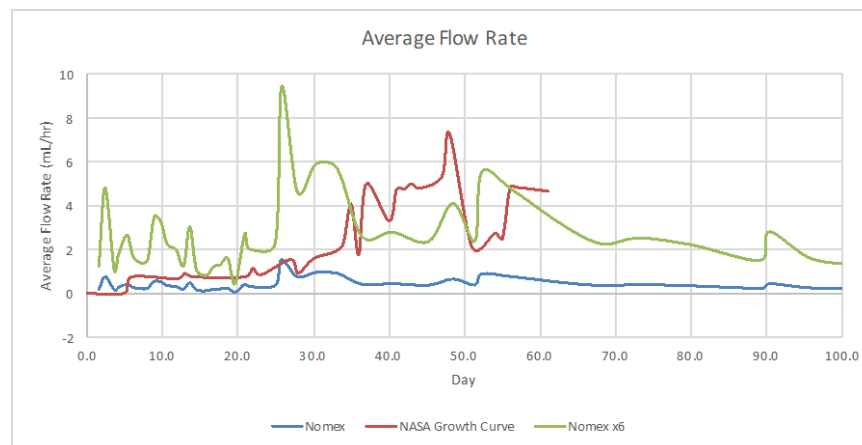


Figure 18: Average flow rate for Nomex samples compared to NASA growth curve.

Cost Analysis

Resource Name	Recipient	Details	Price
Travel	Dr. Ling	\$100/trip assumed ~15 trips throughout the year	\$
Supplies	Students	Experimental materials	\$
	Students	Capillary tubes (donated - Paradigm)	\$
	Students	Growth Media (donated - Ohio State University Athletic Department)	\$
Indirect Costs	University	Cost Rate (54%)	\$
Labor	Students	Summer work to ensure efficacy of project	\$
Total			\$

Table 7: Summary of project expenditures

54% of the allotted budget from the NASA X-HAB Challenge was given to The Ohio State University. This is a standard fee for all externally funded projects. This left the team with \$. Dr. Peter Ling, the advisor to the students working on the group used \$ to travel between Wooster, Ohio (where his office is located) to Ohio State University for meetings and presentations. This left the team with \$. Since the experimentation was extremely simple, only \$ was spent on material costs. This left the team with \$. The remaining funds were given to two team members (Braydi McPherson-Hathaway and Jeddy Choi) to continue working on the project in the summer of 2016 at a standard rate of \$/hour of work. This work included finalizing the AutoCAD models, preparing presentations, organization of reference materials, and training of the 2016-2017 NASA X-HAB team for the project's future success.

Further Design Considerations

On Earth Applications

Despite the original design intentionally made for aeronautical travels, there are ways to use VEGGIE in 1G. Possible commercial models of VEGGIE, focusing on on-demand watering for crop plants or personal gardening at home may be an option for future projects or research. On-demand watering system users could implement different capillary fibers corresponding to different periods of away time. For longer periods of time, Nomex or similar fibers could be used. For shorter periods of time, nylon may be used. The design can be utilized for passive water delivery for user's that are not able to be present every day of plant gestation, allowing profitability as a business venture. Using on-demand watering systems could significantly decrease labor costs in industrial plant growth.

The concept of passive plant growth would also be attractive to consumers at home and in the workplace. Personal on-demand watering systems could be a fun, easy, and sustainable way for people to acquire fresh vegetables and nutrients in unlikely environments. Usage in high work hour per week and/or low income households to grow fresh vegetables without high user input for promotion of a healthy diet that might otherwise be difficult to find access to base on socioeconomic status. This design would also enable the growth of fresh vegetables in areas whose natural environments (such as deserts or tundra regions) are not suitable for certain crops outdoors.

Space Flight Applications

In order to ensure verifiability for space flight, the water reservoir will have to undergo more theoretical evaluation to ensure that the plate angles, number of porous spaces in the plates, location of system relative to how much acceleration the system will experience, and other variables do not present a problem and are correct in their design.

Design Risks

The proposed design alterations to the VEGGIE water delivery system inherently have some design risks. Below is a discussion of design risks foreseen by the Ohio State X-HAB team with a short discussion about each risk.

Single-Interface Capillary Connection

During the PPE, algae growth in the water reservoir (Tupperware containers) and the casing tubes was observed. This design risk can be effectively mitigated by ensuring that no light reaches within the casing tubes or water reservoir. This could be achieved by adding an opaque film around the reservoir and casing tube, or simply designing the system with materials that are inherently opaque. One advantage of having transparent materials in the water reservoir and the casing tubes is that astronauts would be able to observe if water is flowing between the water reservoir and the plant pillow bags. Additionally, a transparent water reservoir with a removable opaque film would allow astronauts to observe the performance of the sponge PMD structure.



Figure 19: Bolting of lettuce after 90 days

Water leakage is a major concern with the new single capillary interface since there is a direct connection between the water reservoir and plant pillow bag via the casing tubes. One primary location of concern is the O-ring seal in the bottom of the plant pillow bag. If this seal rips, it could risk a system leak. Another location of concern is the casing tube connection with the water reservoir, especially after multiple growth cycles using the same system. However, since water does not currently leak out of the opening of the plant pillow bag in the current VEGGIE system, the team does not believe that small holes in the system will result in large system leakage.

Root growth through the casing tubes was observed in the PPE ground tests The Ohio State University. This could pose a problem, especially if microbial or algal growth occurs in the water reservoir as a result of root growth in the water reservoir. It is still unknown what the effect of the root growth in the water reservoir is on plant health. The tests at Ohio State indicated that it had little effect on water uptake, and may have actually assisted the plant in water delivery from the water reservoir into the plant pillow bag. A major concern with root-growth is not on the effect it has on the growing plant, rather it is the effect this may have on cleaning the water reservoir following growth cycles. If root growth is permitted into the water reservoir, there may need to be a procedure for removing the roots following each growth cycle, which would add crew-time. Since root growth was observed in the current VEGGIE system through the two-interface capillary system, it is likely that root growth will be nearly impossible to mitigate in the teams proposed system.

Soil debris was also noticed in the water reservoir during the PPE (see Figure 20). Similar to the plant root-growth, soil debris will have an effect on long term cleanliness of the water reservoir. To prevent soil from passing through the casing tube, the team recommends implementation of a screen on the plant pillow side of the tube. Alternatively, the water reservoir could be flushed out using water from the spacecraft to remove the debris after harvesting plants.



Figure 20: Roots growing into the water reservoir and some noticeable debris.

Another risk of the system is bubble obstruction of the capillary fiber. During plant production experimentation a water tube was added after it was seen that the #13 Three Strand Nomex experiment began showing drought symptoms. The team observed that bubbles had been introduced into the capillary interface when the team was removing the casing tubes from the water

reservoir to refill the water reservoir. Following the insertion of a watering tube, no bubble obstruction issues were seen again. Additionally, the proposed sponge PMD design is designed to mitigate the concern of gas bubbles entering from the water reservoir.

The connection between the casing tube and the water reservoirs sponge PMD may be a weak point in the design, which could lead to a disconnection of a PMD from the casing tube, and possible system failure. This is especially a concern during system set up and priming, as larger forces will be put on the system during the casing tube insertion into the plant pillow bag. To mitigate this issue, it is recommended that the system be strengthened around these critical points by thickening the PMD-casing tube connection point. If a Nomex matted PMD is chosen in the design, the PMD's flexibility may decrease the pressure on the PMD-casing tube connection, increasing the durability of the system connection point.

By incorporating a casing tube insertion on the bottom of the plant pillow, the system losses 1-2 cm of crop headspace, a design risk for the system. This headspace loss could be reduced by further developing the insertion system to lessen the loss, or having the casing tubes be flexible such that they may insert into the side or top of the plant rooting pillows.

Another risk is that the single-interface design has not been proven in microgravity and could fail to work for its' application aboard the ISS. It is recommended that the fabric system be tested in microgravity prior to system production. Theoretically, capillary forces dominate in microgravity, which leads the team to believe that the capillary flow through the single-interface system should perform even better in microgravity. However, there is a risk that it passes too much water, and overwaters the system. The team recommends testing capillary system on the existing VEGGIE software in the case that the two-interface matted version fails. A simple experiment using the fibers could be conducted using a very small amount of Nomex fabric, which is lightweight and wouldn't add much mass to a future launch. Also, since the Nomex already existing on the ISS, future Nomex cord experimentation could use the Nomex from the current system if the current VEGGIE software continues to fail.

Lastly, the single-interface capillary system will likely take more time to assemble for astronauts aboard the ISS. This is due to the 24 insertion points required to complete the system. However, if the system functions continuously as it has in tests at The Ohio State University, there will be an overall decrease in crew time for the system, a major benefit of the proposed system. This

risk could be mitigated by incorporating more fibers into less casing tubes per plant pillow (as seen in Figure 11 casing tube design), though it may introduce more capillary and PMD stability risks.

Sponge PMD Water Reservoir Design

The largest design risk for the sponge PMD water reservoir design is the increase in overall system mass due to the PMD structures. The effect of this overall system mass increase may be reduced by using lightweight polymers or matted Nomex, as discussed in Design Evaluation – PMD Material Selection. Another possibility is to reduce the number of casing tubes bridging the interface. An example of this is presented in Figure 12. Another method to reduce the system mass is to make fins porous so that their mass is decreased. If the PMD fins are porous, it would allow the water to more easily push out gas bubbles that could be trapped at the top side of the water reservoir by creating a more direct flow-path for the water to travel when first inserted into the reservoir. Porous fins would also become more fragile, thereby introducing another design risk. Further evaluation of a porous PMD is recommended in order to balance these two risks.

Another risk of the sponge PMD water reservoir design is vent tube leakage. This would most likely occur just after priming. During priming, as discussed in the concept of operations section, the vent tube should be covered with a towel so that water leakage would not occur. This same technique could be used if water leakage is witnessed by crewmembers in space-flight.

Manufacturing of the sponge PMD water reservoir is considered a design risk due to its highly intricate and complicated design. It is recommended that NASA contacts an external supplier to see if such a PMD web structure may be produced. If an external supplier cannot build the system, the team recommends 3D printing the structure.

As discussed in Design Evaluation – PMD Material Selection, determining the material to be used for the PMD itself presents a large design risk since no similar PMD structure currently exists. The team at Ohio State has narrowed down the options to a matted Nomex or a rigid polymer sponge PMD. It is recommended that NASA contacts PMD experts to determine which material may best fit the VEGGIE application.

A large design risk for the sponge PMD is the crop headspace loss attributed to the PMD structure. In the team's design there is a 0.5 cm gap between the PMD structure and the casing tube insertion into the water reservoir. This gap could be removed, connecting the sponge PMD to the top of the water reservoir, and could possibly reduce the headspace loss due to the PMD from 5 cm to 4 cm, allowing the plant to have a little extra room. Another possibility for reducing crop

headspace loss is to reduce the size of the PMD itself. This would cause the open flow volume of the PMD structure to be reduced, resulting in decreased stability of the system. Further evaluation of PMD sizing is recommended in order to balance these two risks.

If a hybrid PMD is chosen (vane and sponge system integration) one challenge would be that the PMD devices (vane or sponge) may exhibit stronger capillary pull in the system, which could be detrimental for water delivery to the casing tubes if designed incorrectly. For this reason, the team recommends using only a sponge design and to avoid using a hybrid PMD design.

Lastly, since water movement in microgravity is dependent on capillary forces and microgravity influences, the sponge PMD structure risks having more water on some of the sponge PMD structures than other structures in the system. This could lead to possible over-watering or under-watering for some of the plants. The team has attempted to mitigate this issue by incorporating PMD connection points to at least two other PMD structures. However, since capillary movement of water is dependent on relatively small forces, water may favor one PMD structure over another, thereby giving some plants access to more water than others. This design risk must be further investigated. It is recommended that NASA contact PMD experts concerning this issue.

Plant Rooting Pillow

The only change in the plant rooting pillow is switching the bottom Nomex matted fabric out and replacing it with four O-ring insertions. These O-rings are considered low-risk since gaps between the O-ring and the casing tube would be likely to be smaller than the plant insertion point, which currently hasn't had leakage problems.

Conclusions and Recommendations

Water was delivered passively and on-demand in tests performed at The Ohio State University. Fluctuations in water uptake were influenced by both the growth cycles of the plants and the environmental light levels, temperature, and humidity. Plant production experiments produced plants from seeds and harvest using the single-interface Nomex cord capillary delivery system. Even though the delivery mode was changed to capillary fibers, plant growth was also achieved with the use of capillary tubes as the mode of water transport. Some root growth was observed passing through the casing tubes into the water reservoir. Further discussion and testing is needed to determine whether this negatively impacts the system or system operations.

As issues concerning the water reservoir arose, viable options for an enhanced reservoir design were developed and reviewed by NASA sponsors. The improved water reservoir design utilized aspects of propellant management devices, currently used by NASA to ensure fuel availability in microgravity. The water reservoir is difficult to test in 1-g since the gas-liquid interface behaves different on earth than it does in microgravity, where capillary forces dominate over gravitational forces. Further experiments with the design in microgravity may be possible by utilizing reduced-gravity aircraft.

With regard to the fibers and amount of strands that would allow optimal flow rate to the plant needs to be researched more. Nomex cord is recommended to be used due to its performance in plant production experiments. It was also seen in these experiments that greater water delivery may be achieved with the addition of more fibers. In addition to the number of fibers to be used in each casing tube, pore space within the fiber needs to be investigated. Studying the effects of pore space within the fibers will allow for an effective diameter to be discovered that could be used for any fiber materials. The effective diameter is what allows for the flow rate and capillary stability through the fibers.

Future Recommendations

To further ensure the success of the proposed VEGGIE system, the team recommends future research and development to be explored related to the Nomex capillary cord configuration, the casing tube material selection, the PMD structure, and the reusability of the system.

The capillary cord performance may be maximized by investigating the effect of both the amount of Nomex present in each system (how many fibers), as well as the configuration of the Nomex strands (loose or tight braids). From the results observed in the 2015-2016 NASA X-HAB Challenge at Ohio State University, it was seen that “Three Strand Braided Nomex” had the highest performance in multiple experimental sets. It was unknown what the effect of a tight vs. loose braid would be since the team had tight braids in each of the experimental sets. The team recommends testing more than three strands of Nomex in future experiments to determine how it may affect the capillary flow rate. The team also recommends testing looser braids to see the effect it has on the capillary water delivery and capillary stability.

The proposed VEGGIE system features a casing tube for connecting the water reservoir to the plant-rooting pillow. The material to be used for the casing tube was not determined during the 2015-2016 NASA X-HAB Project at Ohio State University. For future development of the system, a food and fire safe material must be selected for the system. The team recommends investigating light-weight polymer materials to avoid increasing the mass of the overall system.

The sponge PMD design for the water reservoir in the proposed system requires more research and development. Specifically, the team recommends investigating the PMD material, the number of fins in the sponge structure, how the PMD will connect to the water reservoir and/or casing tubes, the vane size and placement, the construction and assembly methods, and the number of casing tubes to be used within the water reservoir (which will affect the number of PMD structures required).

Fiber material recyclability needs to be investigated as to help further the life-cycle analysis of the proposed VEGGIE system aboard the ISS. The reusability of the system is the next step after providing consistent water flow to the plant. For reusability, the cleaning, re-priming, and re-attachment of the casing tubes need further analysis.

Outreach and Engagement

During Ohio State University's 2015-2016 NASA X-HAB Challenge presentations were routinely given by the student team members to various audiences.

The entire student team participated in monthly project update presentations for the capstone course in the Food, Agricultural and Biological Engineering (FABE) Department at Ohio State University taught by Dr. Jane Fife. These update presentations were given to an audience of approximately 60 FABE undergraduate students. Two formal presentations were given to IPAG, an engineering accreditation organization, throughout the year. One was delivered as a formal PowerPoint presentation, while the second presentation was delivered as a formal poster presentation at the end of the academic year. In the formal poster presentation, the team received the "most innovative design award."

Outside of the capstone course, three presentations were given. Alex Jensen and Braydi McPherson-Hathaway delivered the first presentation to an Ohio State University student organization called Engineers for a Sustainable World on March 3, 2016. This presentation was given to approximately 20 undergraduate and graduate students within the College of Engineering at Ohio State University. For the second presentation all student team members presented at the Ohio State University's Engineering Capstone Design Poster Showcase on April 26, 2016. This event included over 100 capstone presentations from all engineering majors at Ohio State University, with thousands of guests. The team's final external presentation was given by Alex Jensen, Jeddy Choi, and Braydi McPherson-Hathaway at the Center of Science and Industry (COSI) located in Columbus, Ohio on August 12, 2016 for an event titled "Farm Days." This presentation included a PowerPoint slideshow, two posters (1 research poster and one mission to mars poster), our experimental set up with plants, the current VEGGIE system, and two capillary demonstration experiments geared towards teaching younger kids about capillary action. An estimated 60 guests, ranging from age 4-60 years old, stopped by the set-up table to learn more about the NASA X-HAB Project and the VEGGIE system.

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Appendices

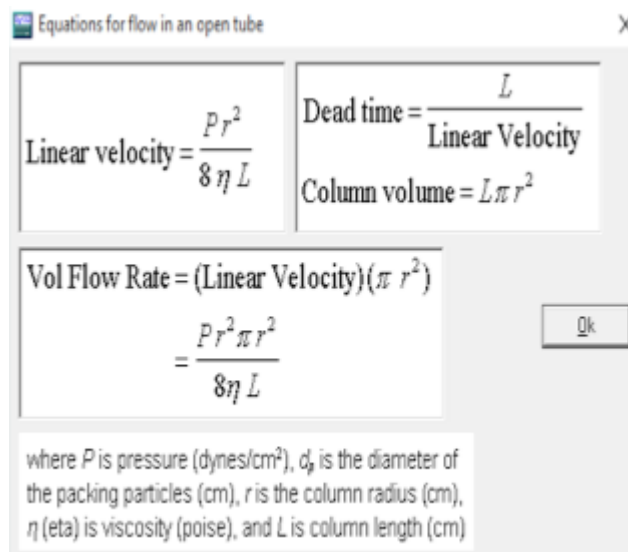
Appendix A: Pugh's Design Matrix of Initial Designs for Capillary Interface

Key Criteria	Weight	Original Design	Design 1	Design 2	Design 3	Design 4
Continuous on demand watering	5	0	1	1	1	1
30 mL/hr watering max	4	0	-1	1	1	1
1 gal tank of contained water	3	0	1	1	1	1
Oxygen must be able to contact roots	5	0	1	-1	1	1
System should last 90 days	3	0	1	1	1	1
1-2 hours per month crew time	3	0	1	1	1	1
Can't have too much pressure on water reservoir	3	0	1	0	0	0
fire hazard	4	0	0	-1	0	0
small capillary tubes smaller than bubble size	5	0	1	1	1	1
Vertically oriented tubes	4	0	0	1	1	1
Non cylindrical capillary structure	3	0	-1	-1	0	0
Soil porosity	3	0	0	0	1	1
Soil absorption rate	3	0	0	0	1	1
Minimal water leakage	3	0	0	1	1	1
equivalent system mass	3	0	0	0	0	-1
Sum of Positives			6	8	11	11
Sum of Negatives			2	3	0	1
Sum of Sames			5	4	4	3
Positives - Negatives			4	5	11	10
Weighted sum of +			27	30	41	41
Weighted sum of -			7	12	0	3
Weighted sum of same			20	12	10	10
Weight positive - Weight negative			20	18	41	38

Figure 21: Pugh's design matrix for initial capillary interface design selection.

Appendix B: Theoretical Calculations to Test Flowrates of Capillary Tubes

The equations below (with variable meanings) were used to calculate the flowrates of the capillary tubes at different states.



Equations for flow in an open tube

$$\text{Linear velocity} = \frac{P r^2}{8 \eta L}$$

$$\text{Dead time} = \frac{L}{\text{Linear Velocity}}$$

$$\text{Column volume} = L \pi r^2$$

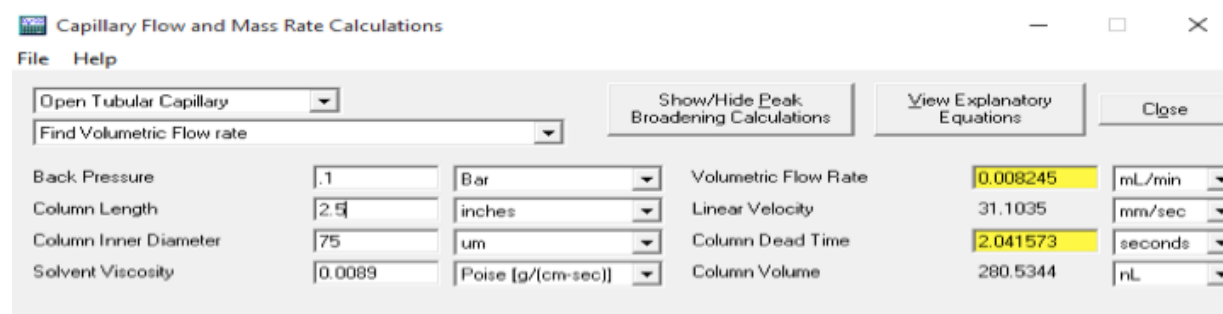
$$\text{Vol Flow Rate} = (\text{Linear Velocity})(\pi r^2)$$

$$= \frac{P r^2 \pi r^2}{8 \eta L}$$

where P is pressure (dynes/cm²), d_p is the diameter of the packing particles (cm), r is the column radius (cm), η (eta) is viscosity (poise), and L is column length (cm)

Figure 22: Equations used in modeling capillary flow discussed in design evaluation – theoretical testing.

The Flow Rate Software Inputs and Outputs are found below:



Capillary Flow and Mass Rate Calculations

File Help

Open Tubular Capillary [v]
Find Volumetric Flow rate [v]

Show/Hide Peak Broadening Calculations [v]
View Explanatory Equations [v]
Close

Back Pressure	0.1	Bar	Volumetric Flow Rate	0.008245	mL/min
Column Length	2.5	inches	Linear Velocity	31.1035	mm/sec
Column Inner Diameter	75	um	Column Dead Time	2.041573	seconds
Solvent Viscosity	0.0089	Poise [g/(cm-sec)]	Column Volume	280.5344	nL

Figure 23: Screen shot of inputs and outputs using the Pacific Northwest National Laboratory, operated by Battelle.

Appendix C: Environmental Considerations and Average Flow Rates

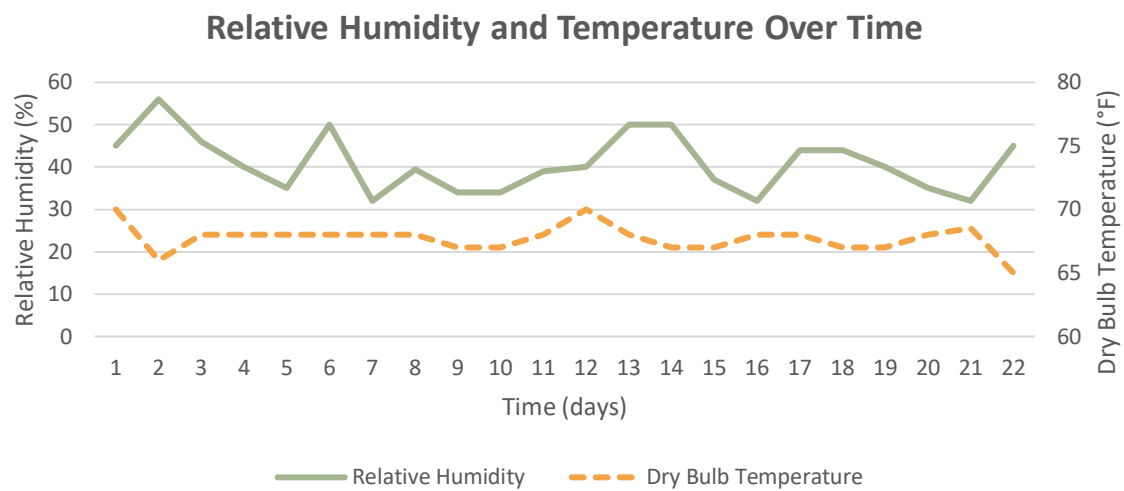


Figure 24: Environmental considerations showing the temperature and relative humidity of the experimental environment.

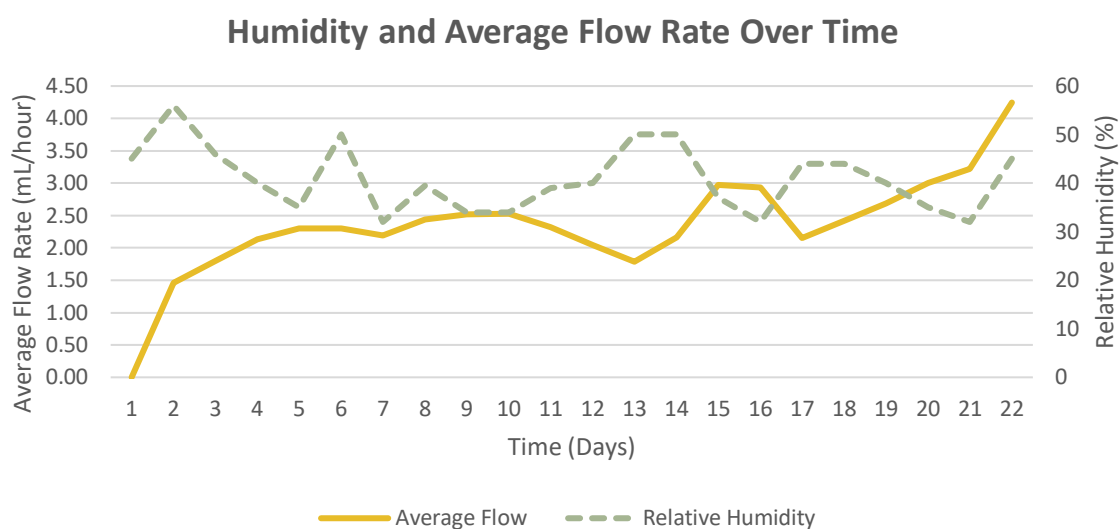


Figure 25: Environmental considerations showing the inverse relationship between relative humidity and the average flow rate of four different materials, three replicates each (12 samples total).

Appendix D: Figures from Results

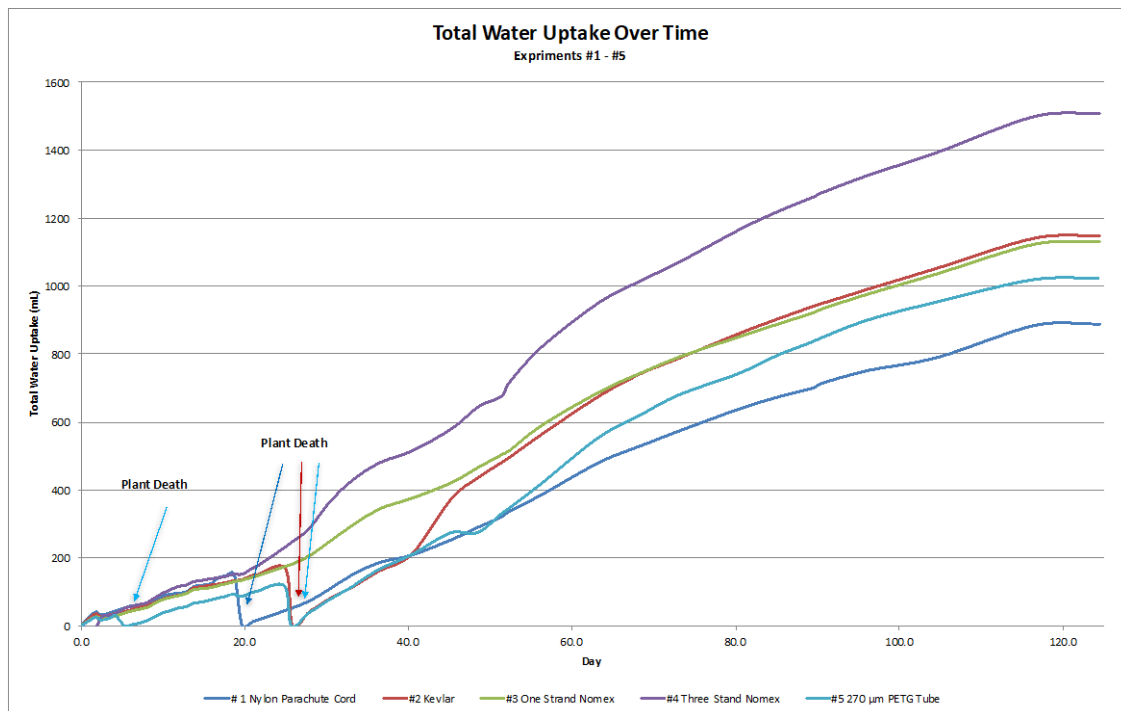


Figure 26: PPE total water uptake over time for experiments #1 - #5



Figure 27: Day 90 – Experiments #1 - #5

From left to right : #1 → #5

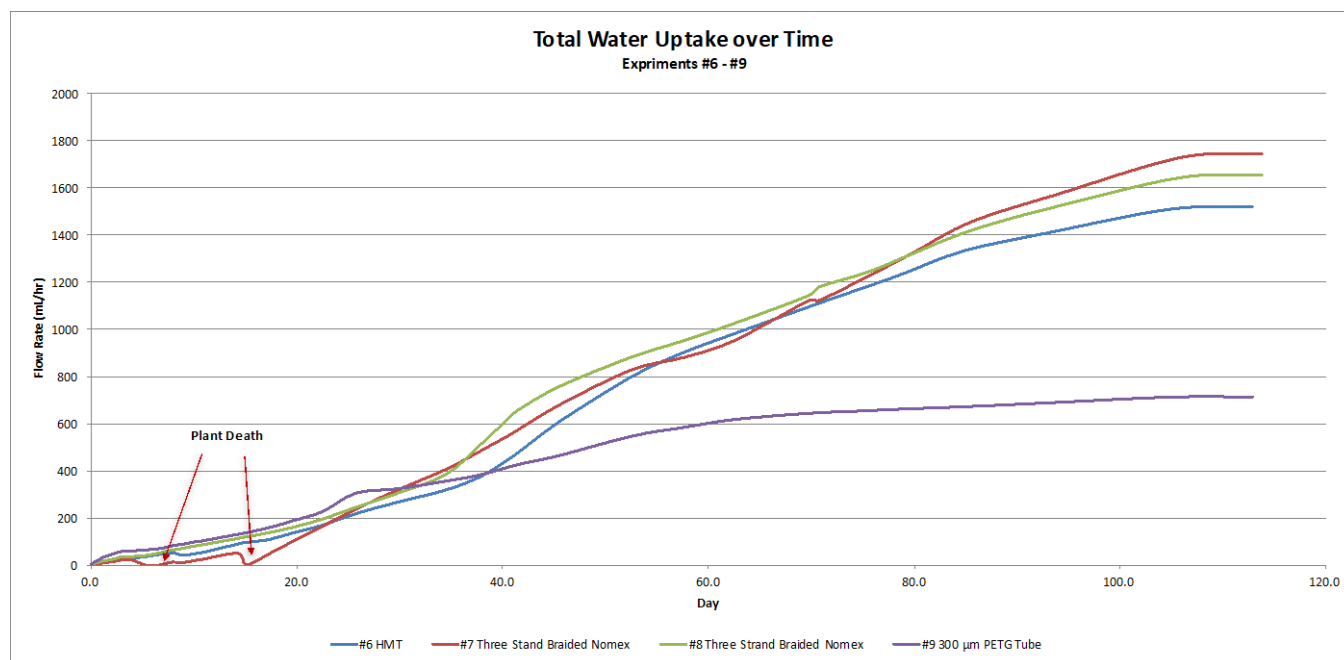


Figure 28: Capillary flow rate over time for experiments #6 - #9



Figure 29: Day 113 – Experiments #6 - #9 (note: plant flowering)

From left to right : #6 #7 #8 #9

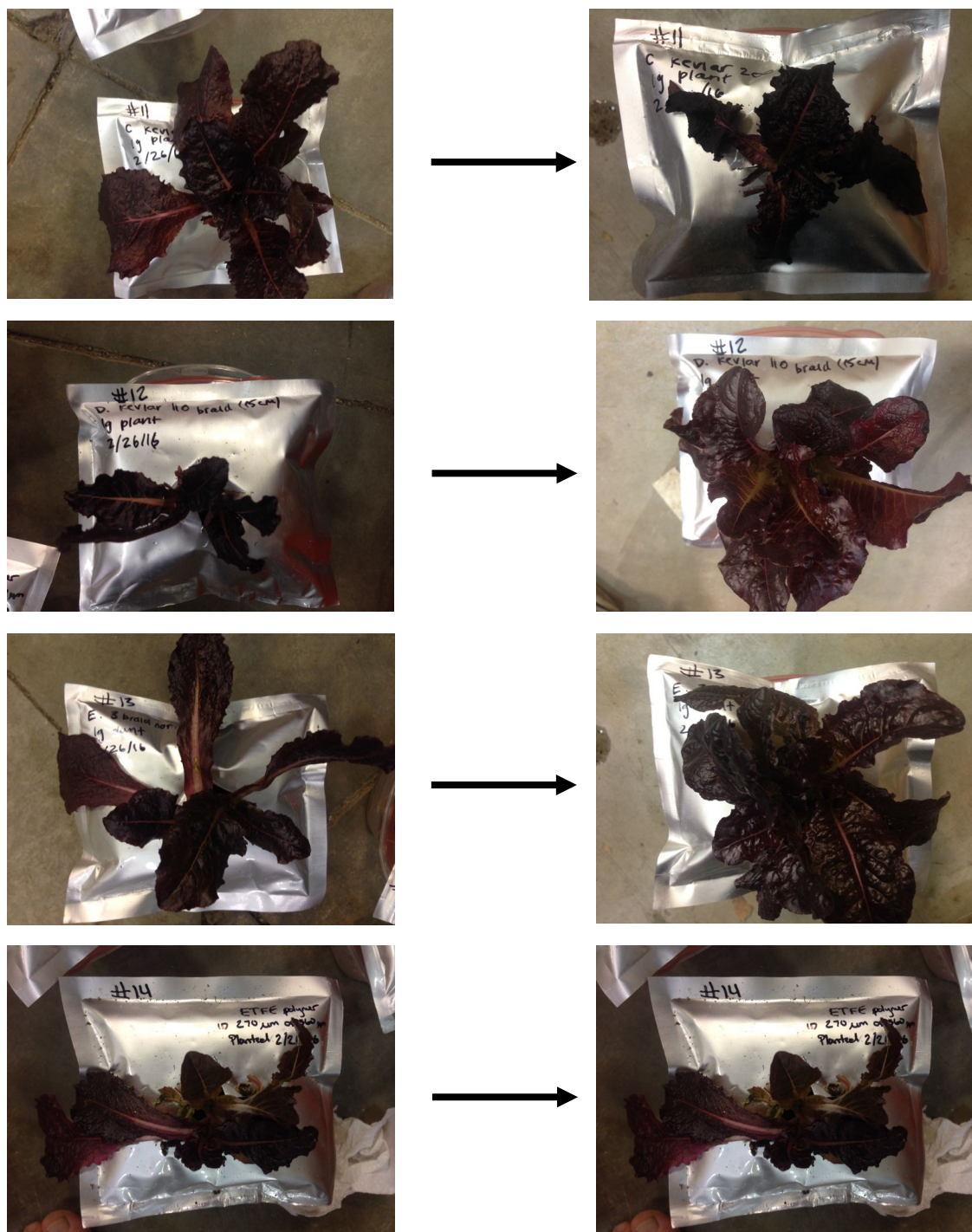


Figure 30: From top to bottom - #11 to #14; left pictures show the day of transplant, right pictures show plant systems two weeks after transplant

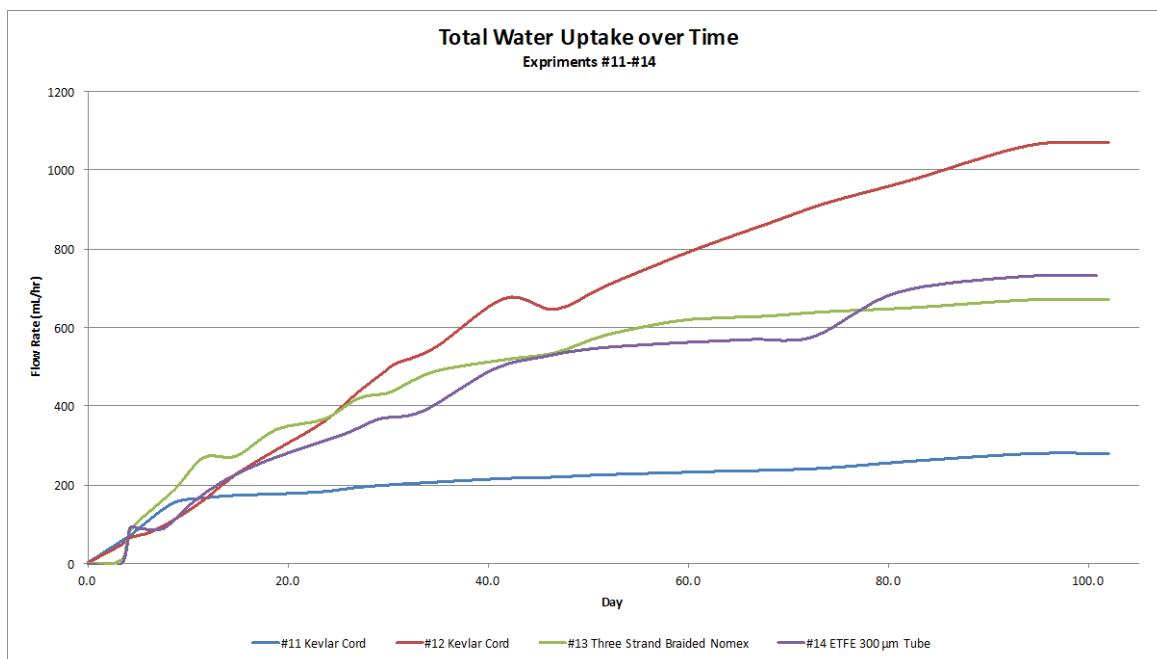


Figure 31: Total water uptake over time for experiments #11 - #14

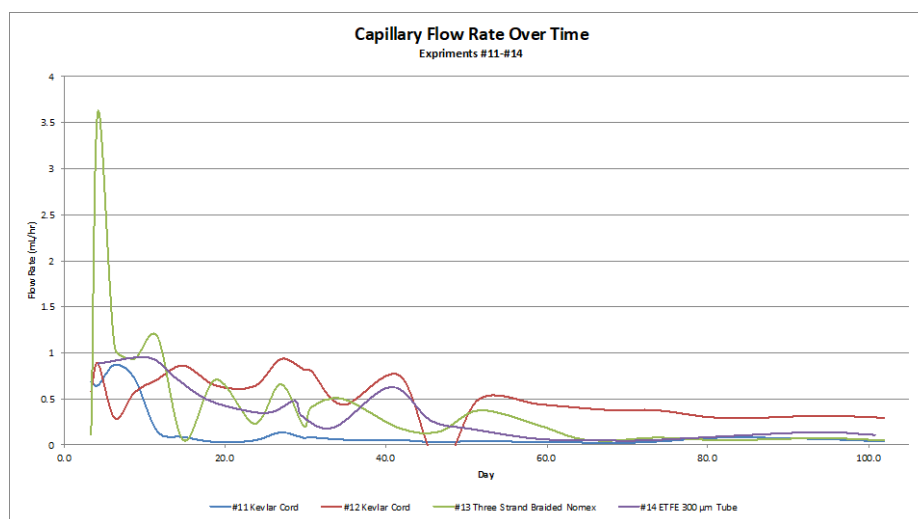


Figure 32: Capillary flow rate over time for experiments #11 - #14



Figure 33: Day 102 – Experiments #11 - #14 and control

from left to right: #11 #14 and control (right)

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