

Investigation of VEGGIE Root Mat

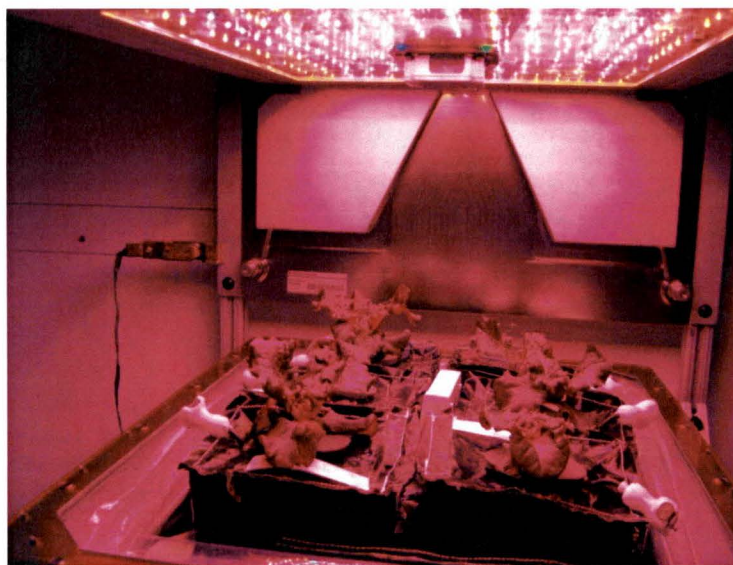
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VEGGIE is a plant growth facility that utilizes the phenomenon of capillary action as its primary watering system. A cloth made of Meta Aramid fiber, known as Nomex is used to wick water up from a reservoir to the bottom of the plants roots. This root mat system is intended to be low maintenance with no moving parts and requires minimal crew interface time. Unfortunately, the water wicking rates are inconsistent throughout the plant life cycle, thus causing plants to die. Over-wicking of water occurs toward the beginning of the cycle, while under-wicking occurs toward the middle. This inconsistency of wicking has become a major issue, drastically inhibiting plant growth. The primary objective is to determine the root cause of the inconsistent wicking through experimental testing. Suspect causes for the capillary water column to break include: a vacuum effect due to a negative pressure gradient in the water reservoir, contamination of material due to minerals in water and back wash from plant fertilizer, induced air bubbles while using syringe refill method, and material limitations of Nomex's ability to absorb and retain water. Experimental testing will be conducted to systematically determine the cause of under and over-wicking. Pressure gages will be used to determine pressure drop during the course of the plant life cycle and during the water refill process. A debubbler device will be connected to a root mat in order to equalize pressure inside the reservoir. Moisture and evaporation tests will simultaneously be implemented to observe moisture content and wicking rates over the course of a plant cycle. Water retention tests will be performed using strips of Nomex to determine materials wicking rates, porosity, and absorptivity. Through these experimental tests, we will have a better understanding of material properties of Nomex, as well as determine the root cause of water column breakage. With consistent test results, a forward plan can be achieved to resolve the issue and give valuable insight for the next generation of VEGGIE.

Nomenclature

A	= cross sectional area
Q	= total discharge
k	= permeability
$P1$	= pressure inside root mat
$P2$	= pressure outside root mat
L	= length of wick
μ	= time step
Rp	= hydraulic pore radius
γ	= generic functions
θ	= height
t	= time index during navigation
H	= height of wicked water level

I. Introduction

Vegetable Production System (VEGGIE) is a deployable system capable of growing plants to provide the ISS crew with a palatable, nutritious, and safe source of fresh food. In the VEGGIE production system, the root mat assembly utilizes the phenomenon of capillary action to mobilize water from the reservoir to the plants roots. A cloth made of Meta Aramid fibers, known as Nomex is used as a wick to transfer the water. The Nomex protrudes into the Teflon PFA perfluoroalkoxy reservoir and is welded into place at the interfaces. The reservoir and wicking

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fabric are protected by a flexible Teflon-coated Kevlar (TCK) enclosure refer to Figure 1 and 2. This enclosure protects the reservoir from abrasion and minimizes light exposure to the reservoir, which limits microbial growth. The reservoir includes a Norprene water fill tube that terminates in a quick-connect coupling. This root mat system is intended to be low maintenance with no moving parts and requires minimal crew interface time. The plant life cycle for the genetically modified lettuce is around 28 days and requires periodic refills of the reservoir. VEGGIE is scheduled to fly to the International Space Station on Space X's Dragon in December 2013.

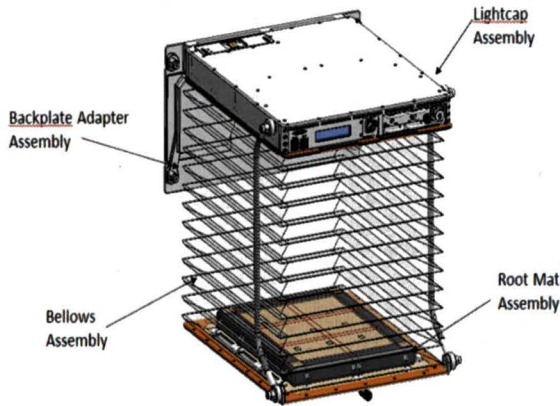


Figure 1: VEGGIE assembly

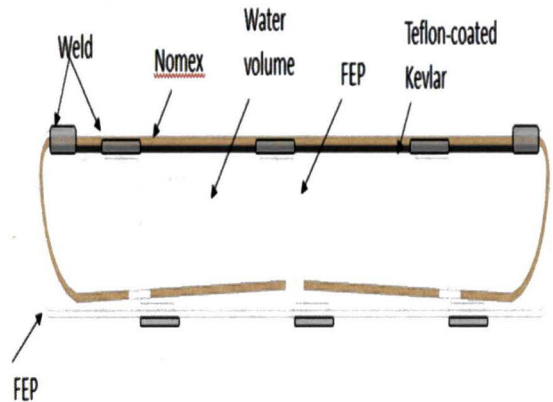


Figure 2: Section view of root mat

Unfortunately, the water wicking rates of the root mat system are inconsistent throughout the plant life cycle. Too much water, over-wicking, is provided to the plants toward the beginning of the cycle, while not enough water, under-wicking, is supplied during the middle of the cycle. This inconsistency of wicking has become a major issue and it drastically inhibits plant growth. Also, the behavior of this root mat system in micro gravity is unknown. The investigation of the fundamentals of capillary action through a porous media is to be studied in order to provide technical support for experimental testing as well as assist in a redesign if needed.

II. Background Research

The investigation began with a thorough background research on properties of wicking materials and capillary flow through a porous media. Several numerical models have been created utilizing Darcy's Law and the Washburn Equation to model this type of flow. Darcy's Law, equation relates viscosity, permeability and pressure drop over a given distance to volume flow rate.

$$Q = \frac{-kA (P_2 - P_1)}{\mu L}$$

Darcy's Law effectively shows how a pressure gradient directly drives flow through a porous media. There are modified versions of Darcy's law, to better incorporate rigid/non-rigid fibers, swelling/shrinking of fibers, and gravity effects. The Washburn Equation assumes that the wicking material will act like a bundle of aligned capillary tubes with the same radius.

$$H = \sqrt{\frac{R_p \gamma \cos(\theta)}{4\mu}} \sqrt{t}$$

The height of the liquid column can be predicted using this method. Incompressible Hagen-Poiseuille flow is assumed and gravity is neglected. Due to lack of time and information regarding porosity, permeability, and swelling effects of Nomex, no CFD model was developed to simulate the problem at hand. However, multiple experimental tests were carried out to try and narrow down the source of the inconsistency of the wicking issue.

III. Experimental Testing

From previous experimental testing and background research a number of probable causes were determined. Due to the severity of under-wicking here on earth, the majority of time was spent addressing this issue. Previously, a Science Verification Test (SVT) was conducted to prove that the root mat concept could provide the needed water for the plants to survive. This test was conducted with some success with the exception that there was a hole at one of the weld joints where water leaked out. However, the plants survived and after the 28 day plant cycle the lettuce was successfully harvested (Figure 3). Yet when the test was replicated with a completely sealed root mat, the Nomex surface became dry half way through the test and massive air bubbles were noticed at the top of the reservoir. More air was present at the end of the test than at the beginning, this lead to the first set of experimental testing to evaluate the pressure gradient inside the root mat. Two different root mats numbered 52 and 54 were used to conduct tests.



Figure 3: SVT full grown lettuce

A. Pressure Testing

One possible theory for the breaking of the water column and decrease in capillary suction is the root mat assembly is a semi rigid body, so as water wicks out hydrostatic pressure decreases, but the root mat does not collapse enough to prevent a vacuum effect from occurring. The theory is that the pressure gradient is what breaks the water column, leaving the wick to dry out on top. To test this hypothesis, a pressure gage was hooked up to a root mat and monitored over a period of four days. A 0-2.5 psid electronic pressure transducer was attached at the bottom of the reservoir to a Quick Disconnect (QD) fitting; therefore the hydrostatic pressure differential was measured. LabVIEW was used to collect and evaluate the incoming pressure data in real time as shown in Figure 4. The trend of decreasing pressure is observed; however, the slight change in pressure is within 1% uncertainty of the pressure transducer. The steady decrease may be attributed to the decrease in height of water or the water being drawn out of the bag and the bag not collapsing to match this decreased volume. Another theory is the fluctuation of pressure is due to the temperature increase from the LED lights turning on and off. Measuring the pressure at the top of the root mat would have been more beneficial; however, there is no location to secure the pressure transducer to at the top of the root mat.

In an attempt to equalize pressure differential in the root mat, a debubbler was hooked up to the QD along with the pressure transducer to allow the root mat to consistently wick. This test was run for four days as well. Unfortunately, no differences were noticed between the two tests, and under-wicking still occurred.

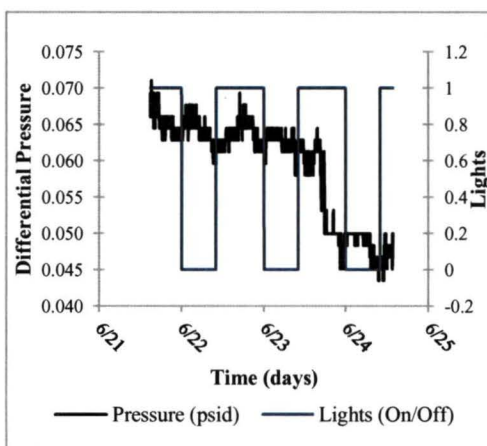


Figure 5: Pressure gradient fluctuation

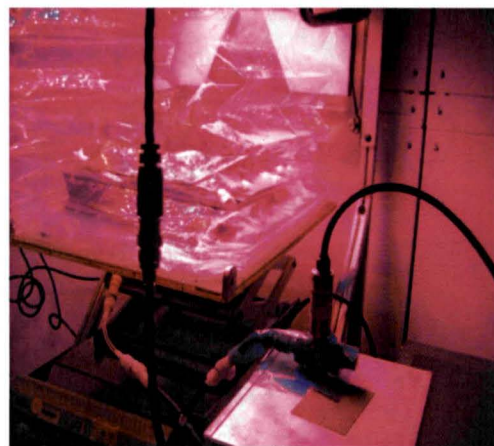


Figure 4: Pressure transducer test set up

B. Refill Testing

During previous experimental testing, two root mats started under-wicking right after the root mat reservoir was refilled using the syringe refill method, Figure 6. A plausible theory surfaced, that the refill method was negatively impacting the capillary action in the Nomex. It was contemplated, the syringe method introduced air bubbles and a

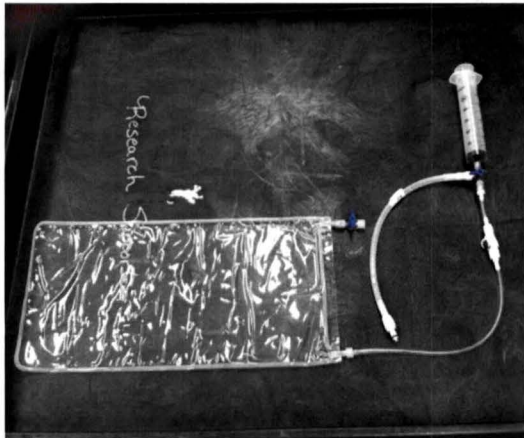


Figure 6: Syringe refill method



Figure 7: Graduated cylinder method

larger pressure gradient into the root mat reservoir. In order to test this theory, the two refill methods were tested. Both root mats 52 and 54 were filled using the graduated cylinder method, Figure 7. The root mats were observed over a three day period exposed to 24°C and 35% relative humidity in the International Space Station (ISS) chamber. Water evaporation and moisture content were recorded for each root mat. At the end of this experiment, the root mats were emptied and dried for a day. Both root mats were then filled again using the syringe method and tested for the course of another three days. Pictures of root mat 54 are shown in Figure 8 over the course of both tests. When closely observed, water lines can be made out on the root mat. It is quickly apparent the wicking is not completely uniform; this may be caused by a non-level table being used. The fact that the root mat never completely wicked was an enormous concern. However, the moisture and evaporation tests for both methods were identical. The manufacturer of the root mat also independently conducted a similar wicking test between the two fill methods;



Figure 8: a) beginning of syringe method b) end of syringe method c) beginning of graduated cylinder d) end of graduated cylinder

Their results are shown in Table 1. Between the combined tests it became more conclusive, that the refill method was not the cause of the under-wicking. Another conclusive data point taken away from this test was the wicking rate almost halved during the extended wick test of over 24 hours. These results influenced a background research of Nomex and its extended wicking properties.

	<i>3hr Fill (ml/hr.)</i>	<i>Refill after 3hr(ml/hr.)</i>	<i>Refill after 3hr(ml/hr.)</i>	<i>Extended wick test (ml/hr.)</i>
Graduated Cylinder	23	22	22	11
Syringe	22	23	22	10

Table 1: ORBITEC wicking rate for different fill methods

C. Nomex properties

During the initial research on the properties of Nomex, it was discovered the current Nomex uses a calendered finishing process, which may negatively affect its water retention capabilities. Calendering is the modification of a surface by applying pressure and heat by passing fabric between heated rotating rollers. The main objectives of

calendering are to reduce thickness by compression, to reduce air permeability by closing threads, and to improve surface finish. It has been proven that long exposure to water or washing the calendered fabric can destroy the glossy surface finish. An extensive test has been conducted between calendered Nomex 410 paper and 411 uncalendered Nomex paper. On average, the 411 retained ten times more water than 410 paper sheets. Through high magnification x-rays it was concluded that uncalendered fabrics have more room to retain water than the calendered Nomex. There are also multiple studies stating that most Nomex is excellent for wicking liquids, but may not retain water well. Also, multiple references researched, discuss the possibility of woven materials swelling or shrinking over time due to prolonged exposure to liquids. A test procedure was written up to test both calendered and uncalendered Nomex and how well it retains water. Due to lack of material and time, the results are not included in this paper.

IV. Conclusion

After conducting these experimental tests, we have a better understanding of the root mat assembly and why the system is not working as intended. However, due to the multiple variables in the system, each variable needs to be tested independently. Depending on results of Nomex properties testing, a more advised decision can be made on a forward plan to solve the root mat's inconstant wicking rates as well as assist towards a redesign.

Appendix

My enthusiasm for space and desire to help further exploration efforts in space motivated me to apply for this NASA engineering internship at the Kennedy Space Center. The idea of being able to contribute to the effort of a self-sustaining plant production system, Vegetable Production System (VEGGIE), intrigued me. Knowing food is a necessity for deep space manned missions and must be grown on route gave me purpose for this project. I believe VEGGIE is the first step towards a sustainable fresh food source in space. I heard about this opportunity through a forwarded email from a friend who attends Purdue University. The email was promoting applications for Propulsion Academy Internship Program, which led me to learn about the OSSI system. My involvement in this project has validated my passion for research and development; furthermore, it has confirmed my interests in fluid and thermal systems. Justifying theories, performing experiments, and solving new problems are what excite me, and this is what I have been able to do at KSC. With this experience under my belt, I can confidently move forward in my academic and professional career.

Acknowledgments

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References

1. Crow, Rita M., and Malcolm M. Dewar. *The Vertical and Horizontal Wicking of Water in Fabrics*. Tech. Ottawa: Defense Research Establishment, 1993. Print.
2. Espinal, Laura. *Porosity and Its Measurements*. Tech. Gaithersburg: John Wiley & Son, 2012. Web. 23 July 2013.
3. Jain, Anjana, and Kalyani Vijayan. "Effect of Penetrants on the Aramid Nomex." *Indian Academy of Sciences* 23.3 (2000): 211-14. Print.
4. Mahadevan, Jagannathan, Mukul M. Sharma, and Yannis C. Yortsos. *Flow-Through Drying of Porous Media*. Rep. 1002 ed. Vol. 10. N.p.: n.p., n.d. Wiley Inter Science, 2006. Web. June-July 2013. <<http://onlinelibrary.wiley.com/>>.
5. Masoodi, Reza, and Krishna M. Pillai. *Darcy's Law-Based Model for Wicking in Paper-Like Swelling Porous Media*. Tech. 9th ed. Vol. 56. N.p.: American Institute of Chemical Engineers, 2010. *Wiley Online Library*. Web. 1 July 2013. <[wileyonlinelibrary.com](http://onlinelibrary.wiley.com/)>.
6. Masoodi, Reza, and Krishna M. Pillai. *Darcy's Law-Based Models for Liquid Absorption in Polymer Wicks*. Publication. 11th ed. Vol. 53. N.p.: AIChE Journal, 2007. *Wiley InterScience*. Web. 1 July 2013. <www.interscience.wiley.com>.

7. Masoodi, Reza, Ph.D, Krishna M. Pillai, Ph.D., and Padma P. Varanasi, Ph.D. *Effect of Externally Applied Liquid Pressure on Wicking in Paper Wipes*. Tech. 3rd ed. Vol. 5. N.p.: n.p., 2010. Print.
8. Nabar, G. M., and G. P. Tawde. *Some Aspects of the Mechanical Finishing of Cotton Textiles*. Tech. N.p.: Textile Institute, n.d. Web. June-July 2013.
9. "Nomex Aramid Fiber Laundering Guide." DuPont, n.d. Web. 19 June 2013.
10. Nystrom, Paul H. *Textiles*. New York: D. Appleton and, 1916. *Google Books*. Web. 26 June 2013.
11. Smeader, Terry. "Cleaning Nomex Fabric." *Cleaning Nomex Fabric*. CoverallSale, 2007. Web. 26 June 2013.
12. Szymkiewicz, Adam. *Modeling Water Flow in Unsaturated Porous Media Accounting for Nonlinear Permeability and Material Heterogeneity*. New York: Springer, 2013. Print.
13. "Technical Guide of Nomex Brand Fiber." N.p., Apr. 1999. Web. 26 June 2013.
14. Wang, J. G., C. F. Leung, and Y. K. Chow. *Numerical Solutions for Flow in Porous Media*. Tech. 27th ed. Vol. 10. N.p.: John Wiley & Sons, 2001. 565-583. Web. 23 July 2013.
15. Whitaker, Stephen. *Flow in Porous Media I: A Theoretical Derivation of Darcy's Law*. Tech. N.p.: D. Reidel, 1986. Web. 23 July 2013.