NASA Technical Memorandum 107546

A Summary of Porous Tube Plant Nutrient Delivery System Investigations From 1985 to 1991.

T. W. Dreschel, C. S. Brown, W. C. Piastuch, and C. R. Hinkle
The Bionetics Corporation
Kennedy Space Center, FL

J. C. Sager, R. M. Wheeler, and W. M. Knott
Biomedical Operations and Research Office
Medical and Environmental Office
John F. Kennedy Space Center, NASA

January 1992

National Aeronautics and
Space Administration

John F. Kennedy Space Center

ACKNOWLEDGEMENTS

This work was performed under contract to the NASA Biological Research and Life Support Office, John F. Kennedy Space Center. We would like to acknowledge the contributions of co-workers with the Controlled Ecological Life Support System Breadboard Project and former SHARP students: Amy Sartain, Valeria Moore, Richard Maxwell, Michelle Fanton, Monica Brown, Heidi Story, and Eva Long. Additionally, we would like to recognize The Bionetics Corporation and the NASA Biomedical Operations and Research Office for critical review of this work and Jean Biscontini for typing the manuscript. This work was performed under NASA contracts NAS10-10285 and NAS10-11624.

---

*The mention of a brand name or vendor does not imply endorsement by NASA or The Bionetics Corporation.

TABLE OF CONTENTS

Abstract

The Controlled Ecological Life Support System (CELSS) Program is a research effort to evaluate biological processes at a one person scale to provide air, water, and food for humans in closed environments for space habitation. This program focuses currently on the use of conventional crop plants and the use of hydroponic systems to grow them. Because conventional hydroponic systems are dependent on gravity to conduct solution flow, they cannot be used in the microgravity of space. Thus, there is a need for a system that will deliver water and nutrients to plant roots under microgravity conditions. The Plant Space Biology Program is interested in investigating the effect that the space environment has on the growth and development of plants. Thus, there is also a need to have a standard nutrient delivery method for growing plants in space for research into plant responses to microgravity. The Porous Tube Plant Nutrient Delivery System or PTPNDS utilizes a hydrophilic, microporous material to control water and nutrient delivery to plant roots. It has been designed and analyzed to support plant growth independent of gravity and plans are progressing to test it in microgravity. It has been used successfully to grow food crops to maturity in an earth-bound laboratory. This document includes a bibliography and summary reports from the growth trials performed at KSC utilizing the PTPNDS.

Introduction:

The use of hydrophilic, microporous membranes to deliver water and nutrients, independent of gravity, to plant roots was proposed by Wright and others (1984, 1988). Development work utilizing this concept at the John F. Kennedy Space Center (KSC) resulted in the design of the Porous Tube Plant Nutrient Delivery System or PTPNDS. Other terms that have been used for the PTPNDS are the Tubular Membrane Plant Growth Unit and the Porous Tube Plant Growth Unit. This system incorporates hydrophilic, microporous materials in the form of a tube to deliver aqueous nutrient solutions to plant roots by capillary action through the pores, contained within an opaque, solid cover to shade and enclose the roots.

Typically, seeds are sown on the surface of the porous tube, within the solid cover which has an opening for shoot emergence. The roots surround the porous tube and receive nutrient solution directly from the surface of this tube. The shoot emerges or is trained through an opening in the solid cover to receive light and carbon dioxide for photosynthesis. A positive displacement pump is used to circulate the solution through the PTPNDS from a reservoir where pH, water, and nutrient levels are controlled. The pump also exerts a slight suction to hold the solution within the tube under accelerated conditions such as in a 1-g environment or within a moving spacecraft. Potential applications for this system are supporting plant space biology investigations in the microgravity of space and for crop production research and crop production in a space station or spacecraft as part of the life support system.

Executive Summary:

The initial design of a scaled-up membrane nutrient delivery system was the Plant Envelope (Fig. 1). This consisted of a sheet of microporous hydrophilic membrane heat sealed to a vinyl backing on which manifolds were produced during the heat sealing process. Screening was placed between the membrane and the vinyl as spacing material to allow solution to flow between. Wheat seed were germinated and grown on this system but a number of problems arose in maintaining the integrity of the seal in the plant envelope due to separation and cracking of the membrane. There were also problems with plant support and local drying of the membrane.

A drastic redesign resulted in the development of the tubular membrane plant growth unit (Fig. 2) which utilized a somewhat tougher membrane than that used previously. This was stitched to form a tube which was supported by a plastic tubular support (skeletal matrix). Pipe fittings were attached to either end and the assembly encased in a PVC pipe with holes or a slit for shoot emergence. Trials T1, T2, T3, T6A, and T8A involved growing wheat on this configuration. Stratified seed were sown directly into the units for germination and subsequent growth. The wheat plants were maintained to maturity and seed production. The phenomenon of decreased plant growth with increased nutrient solution suction was first observed during these trials. Differences in plant growth due to pore size was also observed in trial T8A.

The next development was the replacement of the membrane tube with a rigid porous plastic tube contained in a rigid or foam root containment tube (Fig. 3). Trial T6B with wheat and trial T9P with

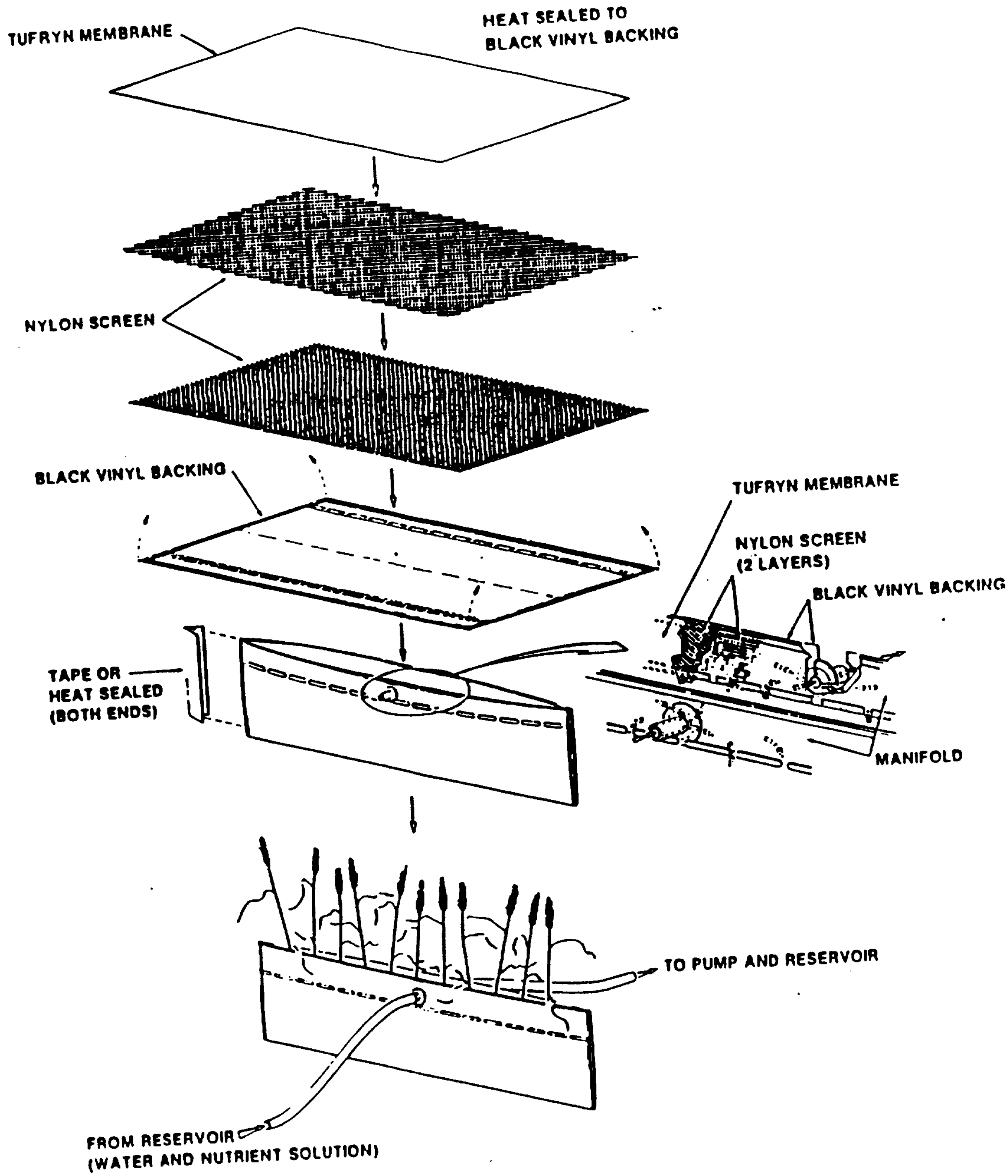

Figure 1. Schematic of the plant envelope for nutrient delivery.

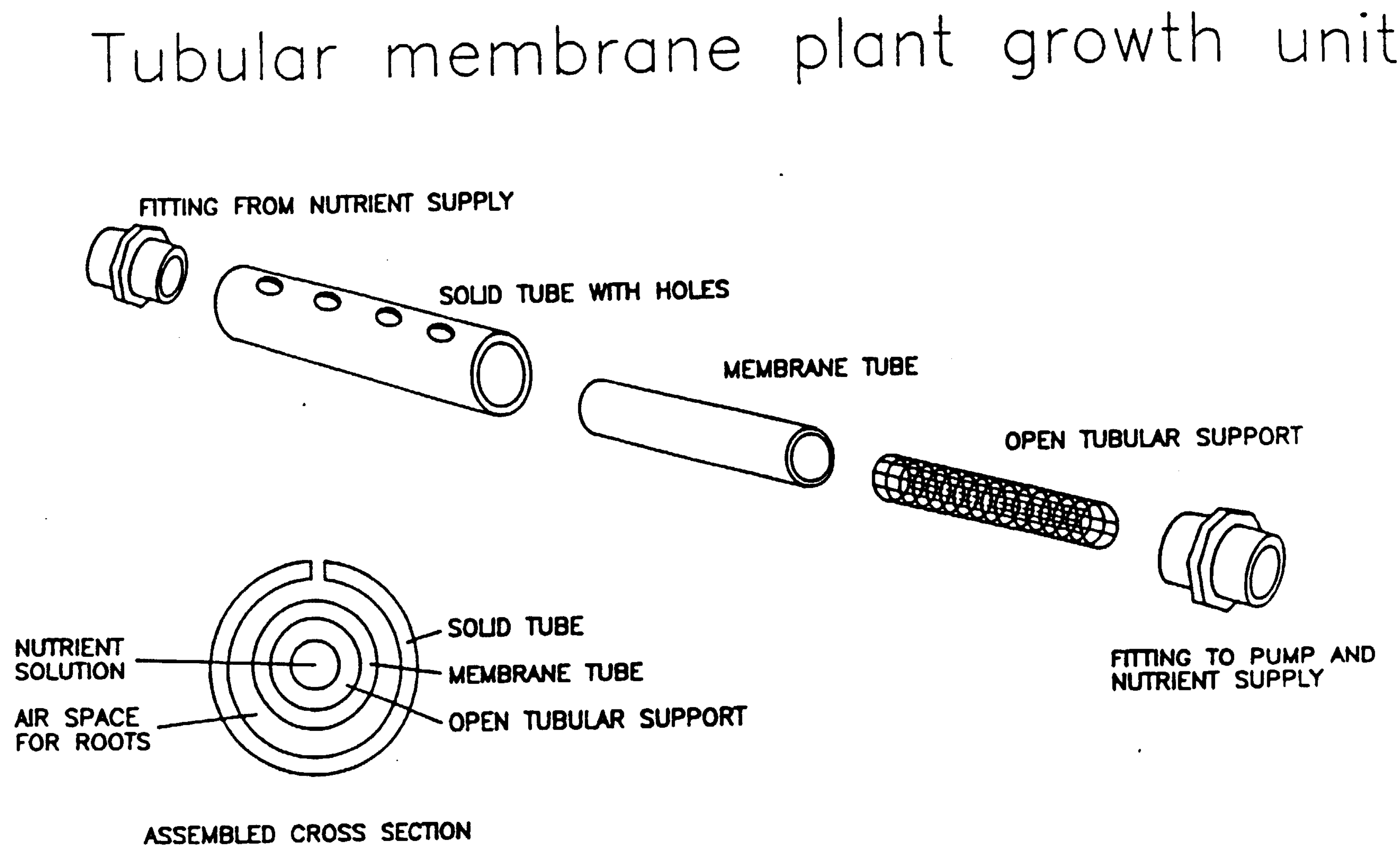

Figure 2. Schematic diagram of the tubular membrane plant growth unit (original design)

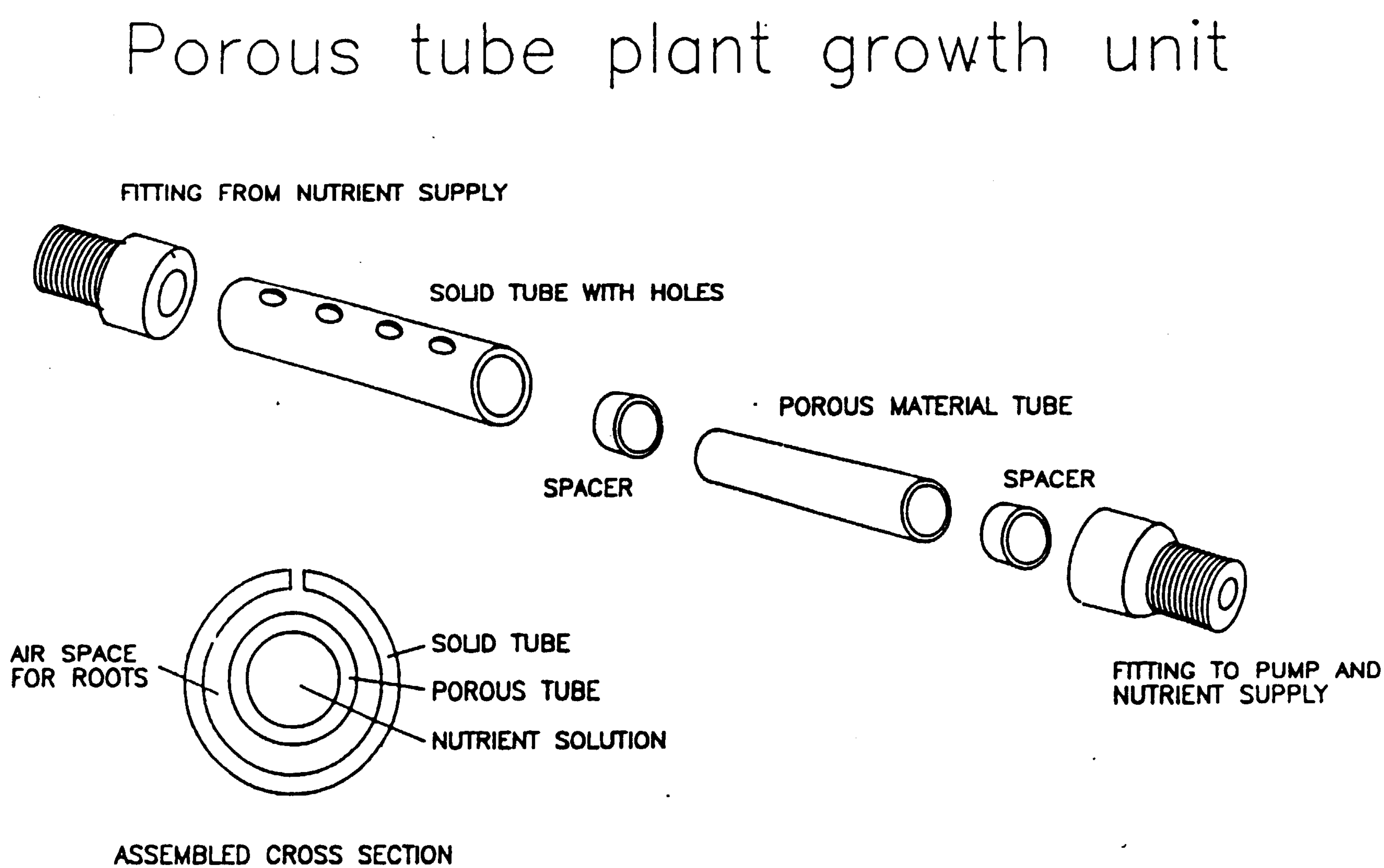

Figure 3. Schematic of the first design of the porous tube plant growth unit.

potato were conducted using this configuration. Stratified wheat seed (T6B) were sown in the units and the plants maintained to maturity with differences in plant growth again observed at different solution suctions. Differential uptake of nutrients at different suctions was also indicated. Potato growth (T9P) was much less than expected which may have been due to the restrictive nature of the root containment tube. The porous plastic material proved to be inadequate as the hydrophilic material within the tube was washed out after the first few uses, making the tube hydrophobic.

The most recent design utilizes porous ceramic tubes and a white/black polyethylene root cover (Fig. 4). Trials T10L, T11L, T12L, T13L, and T14L with lettuce; trial T15S with soybean; trial T16T with tomato; and trials T17R, T18R, T19R, and T20R with radish were all conducted with this configuration. The ceramic tubes have proven to maintain their hydrophilic nature and the root wrap maintains a moist environment for the roots which surround the ceramic tube. The lettuce trials have indicated possible suction effects on growth and planting density effects. The soybean, tomato, and radish trials were successful in testing the ability of the system to support the growth of these crops. Further work is indicated to identify areas of improvement to increase plant production.

The appendix contains summary reports from each of these growth trials conducted between 1985 and 1991 which include a description, objectives, results, conclusions/comments, and tables. A bibliography is also included which lists documents describing these and other PTPNDS investigations in greater detail.

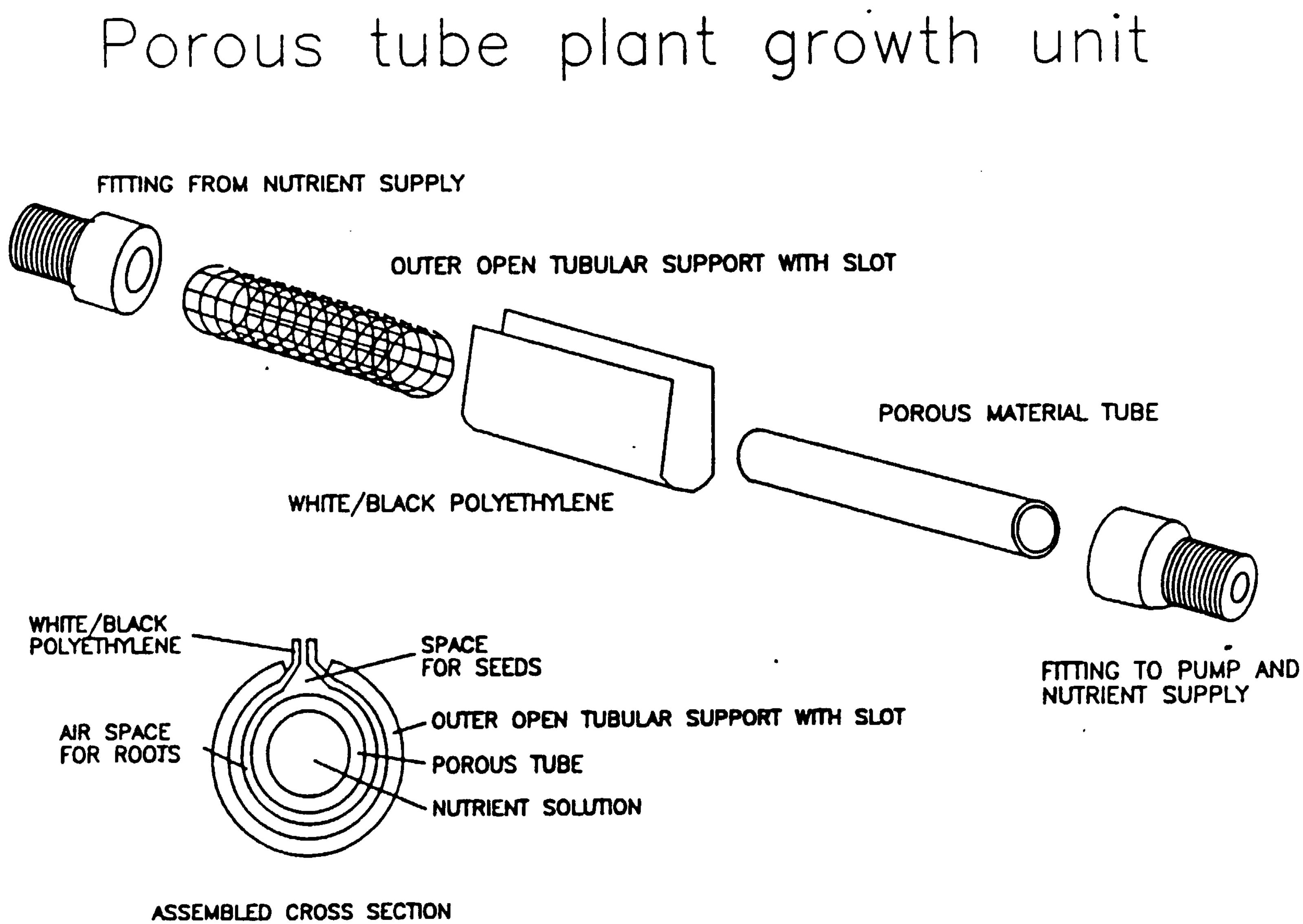

Figure 4. Schematic diagram of the second design of the porous tube plant growth unit.

Appendix

TUBULAR MEMBRANE TRIALS T1 - T3

Investigator (s): T. W. Dreschel   Date: 1/85 - 9/86

Species (crop)/Cultivar: *Triticum aestivum* cv. Yecora rojo

Env. Conditions: Temp.: 23 C RH: 65% PPF: 350 umol/s/m2

Photoperiod: Continuous   CO2: ambient Other: ambient

Experiment Objective: To develop and test a nutrient delivery system designed to supply water and nutrients to plants in space.

Results:

The tubular membrane plant growth unit was successfully operated in the first three trials described herein with wheat grown from seed to harvest. Summary tables of the harvest results from these trials are included as Tables 1,2, and 3. All plants were grown within plant growth chambers on a recirculating nutrient solution which was maintained throughout the trial.

Conclusions/Comments:

It was determined from these trials that the tubular membrane plant growth units could supply plant roots and produce wheat at rates within the expected ranges of field-grown and that grown in other hydroponic systems. These trials also demonstrated the need to monitor and control the suction used to contain the solution within the porous membrane.

....

Table 1. Results of wheat harvests from tubular membrane plant growth unit trial T1.

Harvest Variable	
Number of plants	15
Number of heads	51
Seed number	915
Total seed mass (gdw)*	36.41
Seed mass/plant (gdw)	2.43
Mass/seed (gdw)	0.040
Total mass/plant (gdw)	4.28
Harvest index (seed/total)	0.57
Number of membrane units	2
Length of units (cm)	30
Estimated suction** (mm of water)	80

* (gdw) = grams dry weight.
** Suction estimated from the differences between the elevation of the membrane units and the surface of the nutrient solution.

Table 2. Results of wheat harvests from tubular membrane plant growth unit trials T2.

Harvest Variable	
Number of plants	97
Number of heads	163
Seed number	2805
Total seed mass (gdw)*	102.1
Seed mass/plant (gdw)	1.05
Mass/seed (gdw)	0.036
Total mass/plant (gdw)	2.28
Harvest index (seed/total)	0.46
Number of membrane units	6
Length of units (cm)	50
Estimated suction** (mm of water)	120

* (gdw) = grams dry weight.
** Suction estimated from the differences between the elevation of the membrane units and the surface of the nutrient solution.

....

Table 3. Results of wheat harvests from tubular membrane plant growth unit trials T3.

Harvest Variable	
Number of plants	243
Number of heads	249
Seed number	2709
Total seed mass (gdw)*	77.05
Seed mass/plant (gdw)	0.317
Mass/seed (gdw)	0.028
Total mass/plant (gdw)	0.678
Harvest index (seed/total)	0.47
Number of membrane units	10
Length of units (cm)	60
Estimated suction** (mm of water)	400

* (gdw) = grams dry weight.
** Suction estimated from the differences between the elevation of the membrane units and the surface of the nutrient solution.

TUBULAR MEMBRANE TRIAL T6A

Investigator (s): T. W. Dreschel Date: 9/87

Species (crop)/Cultivar: *Triticum aestivum* cv. Yecora rojo

Env. Conditions: Temp.: 18/16 C RH: 65% PPF: 350 umol/s/m2

Photoperiod: 18-L/6-D CO2: ambient Other: ambient

Experiment Objective: To evaluate the effects of the suction used to contain nutrient solution within the membrane tube on plant growth. Nine tubular membrane units (three replicates, three pressure treatments) were used to do this.

Results:

The harvest results corresponding to the different suction treatments, averaged over the treatments, are presented in Table 1. There was a general trend of decreased plant and seed biomass with higher suction, but not statistically significant.

Conclusions/Comments:

Under the given environmental conditions and the low range of suctions used, there appeared to be a general decrease of seed and total biomass but there was not a statistically significant difference between treatments.

The HI was surprisingly stable 0.51 vs. 0.49 vs. 0.50.

....

Table 1. Harvest results from experiment T6A. Each treatment included three tubular membrane units.

Harvest Variable	Treatment 1 (45 mm water)	Treatment 2 (85 mm water)	Treatment 3 (170 mm water)
Number of plants	85	106	92
Number of heads	136	136	117
Total seed mass (gdw)	130.3	125.2	109.9
Seed mass/plant (gdw)	1.53	1.18	1.19
Mass/seed (gdw)	0.034	0.031	0.034
Total mass/plant (gdw)	3.01	2.40	2.37
Harvest index (HI)	0.51	0.49	0.50

POROUS TUBE TRIAL T6B

Investigator(s): T. W. Dreschel Date: 12/87

Species (crop)/Cultivar: *Triticum aestivum*, cv. Yecora rojo

Env. Conditions: Temp.: 18/16 C RH: 65% PPF: 350 umol/s/m2

Photoperiod: 18-L/6-D CO2: ambient Other: ambient

Experiment Objective: To test the effects of suction on wheat grown using the 1/2" PVC size Porex with a 1" schedule 40 PVC outer sheath and holes for plant emergence. Nine porous tube units (three replicates, three pressure treatments) were used to do this.

Results:

Significant differences were found in a number of variables dependent on the suction exerted (Table 1). Straw mass, chaff mass, seed mass and total mass per plant were affected as well as the number of seeds per plant and per primary head. Less biomass and fewer seeds were produced with increased suction. Chemistry of the "root solution" (solution held among the roots by capillary forces) differed from that of the solution in the reservoir (Table 2). It is not clear if this was a function of the suction and/or was due to some selectivity by the plant roots as to water and dissolved ions.

Conclusions/Comments:

Control of suction is critical when using this configuration of the porous tube plant growth units as the magnitude of the pressure appears to directly affect growth. Further work in this area using other configurations is continuing.

....

Table 1. Harvest results from experiment T6B. Each treatment included porous tube units.

Harvest Variable	Treatment 1 (41 mm water)	Treatment 2 (155 mm water)	Treatment 3 (267 mm water)
Number of plants	112	105	111
Number of heads	247	262	223
Total seed mass (gdw)	367	198	203
Seed mass/plant (gdw)	1.72	0.91	0.90
straw mass/plant (gdw)	0.79	0.48	0.41
chaff mass/plant (gdw)	0.49	0.29	0.27
root mass/plant (gdw)	0.28	0.20	0.24
Mass/seed (gdw)	0.042	0.042	0.047
Total mass/plant (gdw)	3.28	1.89	1.83
Harvest index	0.52	0.48	0.49

Table 2. Mean concentrations (mg/L) of elements in the reservoir and root mass solution in each treatment (N=3) from experiment T6B.

Element	Reservoir	Treatment 1 (41 mm H2O)	Treatment 2 (155 mm H2O)	Treatment 3 (267 mm H2O)
Nitrate-nitrogen	79.2	0.2	68.8	72.9
Calcium	129	380	341	355
Potassium	121	467	322	391
Phosphate-phosphorus	>0.02	30.4	20.1	17.6
Magnesium	59.0	163	118	154
Copper	>0.02	0.4	0.3	0.3
Manganese	0.11	2.67	0.70	0.73
Zinc	0.19	2.27	1.42	1.72
Iron	1.58	13.7	11.5	16.9

TUBULAR MEMBRANE TRIAL T8A

Investigator(s): T. W. Dreschel   Date: 4/88

Species (crop)/Cultivar: *Triticum aestivum* cv. Yecora rojo

Env. conditions: Temp.: 18/16 C RH: 65% PPF: 300 umol/s/m2

Photoperiod: 18-L/6-D   CO2: ambient Other: ambient

Experiment Objective: To evaluate the effects of the suction used to contain nutrient solution within the membrane tube, the pore size of the porous material, tube configurations and diameters, and placement of the unit (edge or non-edge) on plant growth. Twenty tubular membrane units with three replicated (or in the case of edge units, two replicates) of three suction treatments with Versapor (0.2 um) of 40, 150 and 300 mm of water, one treatment of Versapor (5.0 um) at 40 mm of water, one treatment of Porex tubes (20 um) with a 1.9 cm O.D. contained in a 2.5 cm I.D. PVC pipe at 40 mm of water, one treatment of Porex tubes (20 um) with a 2.5 cm O.D. contained in a 3.1 cm I.D. at 40 mm of water, and the edge effect treatment of Versapor (0.2 um) at 40 mm of water.

Results:

The means of the harvest results corresponding to the different suction treatments are presented in Table 1. Significant differences were found for the following variables: Spikelet number per primary head, seed number per primary head, seed number per plant-total, primary seed dry weight per plant, seed dry weight per plant, root dry weight per plant, chaff dry weight per plant, straw dry weight per plant, total dry weight per plant, primary head fresh weight per plant, other heads fresh weight per plant, root fresh weight per plant, straw fresh weight per plant, and total fresh weight per plant. Duncan Groupings of the treatments are also presented.

The harvest results corresponding to the different pore size treatments, means and standard error, are presented in Table 2. Significant differences were found for the following variables: Spikelet number per primary head, seed number per primary head, seed number per other head, seed number per plant-total, primary seed dry weight per plant, other seed dry weight per plant, seed dry weight per plant, chaff dry weight per plant, straw dry weight per plant, total dry weight per plant, primary head fresh weight per plant, other heads fresh weight per plant, straw fresh weight per plant, and total fresh weight per plant.

There were no significant differences between the two diameters of Porex tube for any of the variables.

Table 1. Harvest data from the suction treatments of experiment T8A. Duncan groupings are given in parentheses and means with the same letter were not significantly different at alpha = 0.05.

Harvest Variable	Treatment 1 (40 mm H2O)	Treatment 2 (150 mm H2O)	Treatment 3 (300 mm H2O)
Spikelets/primary	16.7 (A)	15.8 (A)	14.1 (B)
Spikelets/other	15.4 (ns)	12.8 (ns)	12.2 (ns)
Seed no./primary	18.8 (A)	16.5 (A)	12.9 (B)
Seed no./other	7.7 (ns)	3.9 (ns)	4.4 (ns)
Primary seed gdw/plant	0.78 (A)	0.67 (A)	0.48 (B)
Other seed gdw/plant	0.29 (ns)	0.15 (ns)	0.07 (ns)
Seed gdw/plant	1.07 (A)	0.82 (B)	0.66 (B)
Root gdw/plant	0.34 (A)	0.21 (B)	0.19 (B)
Chaff gdw/plant	0.34 (A)	0.29 (AB)	0.25 (B)
Straw gdw/plant	0.87 (A)	0.56 (B)	0.45 (C)
Total gdw/plant	2.48 (A)	1.88 (B)	1.55 (B)
Primary head gfw*/plant	1.93 (A)	1.50 (B)	1.01 (C)
Other heads gfw/plant	0.79 (A)	0.38 (B)	0.09 (C)
Root gfw/plant	5.63 (A)	3.53 (B)	2.50 (C)
Straw gfw/plant	2.47 (A)	1.47 (B)	0.99 (C)
Total gfw/plant	10.83 (A)	6.89 (B)	4.59 (C)

*gfw = grams fresh weight

....

Table 2. Harvest data from the pore size treatments of experiment T8A. Significant differences (alpha = 0.05) are denoted with by "S".

Harvest Variable	Treatment 1 0.2 micron (40 mm H2O)	Treatment 4 5.0 micron (150 mm H2O)	
Spikelets/primary	16.7	17.4	S
Spikelets/other	15.4	16.3	
Seed no./primary	18.8	33.0	S
Seed no./other	7.67	41.4	S
Primary seed gdw/plant	0.78	1.28	S
Other seed gdw/plant	0.29	1.57	S
Seed gdw/plant	1.07	2.85	S
Root gdw/plant	0.34	0.33	
Chaff gdw/plant	0.34	0.74	S
Straw gdw/plant	0.87	1.48	S
Total gdw/plant	2.48	5.40	S
Primary head gfw/plant	1.93	2.97	S
Other heads gfw/plant	0.79	3.89	S
Root gfw/plant	5.63	5.53	
Straw gfw/plant	2.47	4.80	S
Total gfw/plant	10.8	17.2	S

The harvest results for edge effects, means and standard error, and presented in Table 3. Significant differences were found for the following variables: Seed number per other heads, other seed dry weight per plant, chaff dry weight per plant. straw dry weight per plant, total dry weight per plant, other heads fresh weight per plant, and straw fresh weight per plant.

Conclusions/Comments:

As in Experiment T6B with Porex tubes, there was a significant suction effect on plant growth in the Versapor (0.2 um) membrane tubes. There also was a significant pore size effect for the units operated at the same suction. Edge effects were evident and probably due to side lighting and better air flow on the outside of the canopy. The two size Porex tubes had very low yield, probably due the porous tube/containment pipe configuration allowing for a greater opportunity for root drying, slowing growth and thus these plants were shaded out by the others. The fact that the Porex tube plants were smaller was probably responsible in part for the lack of significant differences. A redesign of the containment tubes for the rigid Porex (or ceramic) tubes is now in testing and shows some promise in replacing the Versapor tubes with rigid Porex or ceramic tubes.

....

Table 3. Harvest data from the edge effects treatments of experiment T8A. Significant differences (alpha = 0.05) are denoted with by "S".

Harvest Variable	Treatment 1 middle 0.2 micron (40 mm H2O)	Treatment 5 edge 0.2 micron (150 mm H2O)	
Spikelets/primary	16.7	17.1	
Spikelets/other	15.4	15.1	
Seed no./primary	18.8	17.1	
Seed no./other	7.67	12.9	S
Primary seed gdw/plant	0.78	0.70	
Other seed gdw/plant	0.29	0.49	S
Seed gdw/plant	1.07	1.19	
Root gdw/plant	0.34	0.33	
Chaff gdw/plant	0.34	0.46	S
Straw gdw/plant	0.87	1.15	S
Total gdw/plant	2.48	3.20	S
Primary head gfw/plant	1.93	1.70	
Other heads gfw/plant	0.79	1.40	S
Root gfw/plant	5.63	5.75	
Straw gfw/plant	2.47	3.15	S
Total gfw/plant	10.8	12.0	

POROUS TUBE TRIAL T9P

Investigator(s): T. W. Dreschel Date: 4/88

Species (crop)/cultivar: Solanum tuberosum, L cv. Norland

Env. Conditions: Temp.: 18/16 C RH: 65% PPF: 350 umol/s/m2

Photoperiod: 18-L/6-D CO2: ambient Other: ambient

Experiment Objective: To grow potatoes using the porous tube plant growth unit, utilizing a flexible containment tube made from closed-celled foam which would allow expansion for tuber formation.

Results:

Harvest results are compared to a previous trial with a rigid containment tube and with results obtained in a more "typical" substrate (peat-vermiculite) in Table 1. The growth of the two plants was extremely slow relative to "normal" plants grown in peat-vermiculite (Wheeler and Tibbitts, 1987) at the University of Wisconsin (UW). Total plant dry weight was about one-tenth of that obtained at 64 days at UW. The flexible tube plants exhibited growth rates similar to those grown in the rigid containment tubes. The harvest index (% tuber biomass) for the flexible tubes was up to 24% higher than either those grown in peat-vermiculite or in the rigid tubes.

Conclusions/Comments:

It is still not clear what is causing the reduced growth rate of potatoes in the porous tube plant growth units. Restricted space or inadequate water and nutrient availability to the roots may have contributed. It is evident that further work is required to adapt a porous substrate system to potato production if better growth is to be achieved.

Table 1. Harvest values for potatoes grown in peat-vermiculite and in the PTPNDS, with a rigid outer containment tube and a flexible (closed cell foam) outer containment tube. Plants were all harvested at 64 days.

	Rigid Tube #1	Rigid Tube #2	Flex-Tube #1	Flex-Tube #2	Peat-Verm #1*	Peat-Verm #2*
Tuber gfw	18.5	27.5	10.2	48.1	474	724
Tuber gdw	4.3	5.9	2.1	9.8	62	114
Shoot gdw	2.8	3.4	0.4	3.3	57	106
Total gdw	8.6	10.5	2.9	14.1	121	228
HI**	0.50	0.57	0.74	0.69	0.51	0.50

*From Wheeler, R. M., and T. W. Tibbitts. 1987. Utilization of potatoes for life support systems in space: III. Productivity at successive harvest dates under 12-H and 24-H photoperiods. Am. Pot. J. 64:311-320.

**HI = harvest index or edible biomass/total biomass.

POROUS TUBE TRIALS T10L-T14L

Investigator(s): T. W. Dreschel   Date: 9/89

Species (crop)/Cultivar: *Lacutuca sativa* cv. Grand Raids

Env. Conditions: Temp.: 20 C RH: 65% PPF: 230 +/- 40 umol m-2s-1

Photoperiod: 24-h CO2: 700 ppm Other: Vita-Lite fluorescent

Experiment Objective: Determine the effects of using a membrane substrate and the effect of its area (Plants/unit area of tube surface) on 28 day lettuce growth rates. In the final two trials, the effect of using a closed-loop bladder system without a standpipe was tested.

....

Table 1. Results of Trial T10L, lettuce grown on the PTPNDS and on porous stainless steel plates. Suction in tubes = 2.0 cm H2O, pressure in plates = 1 cm H2O, PPF = 190 umol/m2/sec. (May, 1989)

	Top gfw	Top gdw	Root gdw
Tube 1a	42.2	3.49	0.85
1b	28.6	2.34	0.85
1c	29.8	2.46	0.85
Tube 2a	12.6	1.07	0.36
2b	13.8	1.23	0.36
2c	14.2	1.31	0.36
2d	9.7	0.99	0.36
2e	5.2	0.56	0.36
Plate 1a	32.5	2.34	0.83
1b	28.8	2.02	0.83
1c	46.4	3.19	0.83
1d	43.0	2.98	0.83
Plate 2a	22.2	1.67	0.67
2b	36.1	2.62	0.67
2c	22.8	1.69	0.67
2d	23.4	1.88	0.67
Plate 3a	41.5	3.18	0.75
3b	35.8	2.69	0.75
3c	35.9	2.38	0.75
3d	40.4	2.89	0.75

Table 2. Results of Trial T11L (density study). Suction in PTPNDS = 2.0 cm H2O, PPF = 270 umol/m2/sec. (June, 1989)

		Top gfw	Top gdw	Root gdw
Tube	1a	28.8	1.82	0.3
Tube	2a	68.6	3.85	0.49
	2b	46.1	2.66	0.49
Tube	3a	59.6	3.25	0.45
	3b	53.6	2.76	0.45
	3c	64.1	3.64	0.45
Tube	4a	19.9	1.11	0.21
	4b	39.6	2.17	0.21
	4c	27.2	1.49	0.21
	4d	37.6	2.13	0.21
Tube	5a	15.3	1.06	0.26
	5b	25.6	1.48	0.26
	5c	31.1	1.83	0.26
	5d	50.8	3.04	0.26
	5e	8.8	1.50	0.26

....

Table 3. Results of Trial T12L (density study). Suction in PTPNDS = 2.0 cm H2O, PPF = 250 umol/m2/sec. (July,1989)

		Top gfw	Top gdw	Root gdw
Tube	1a	26.8	2.83	0.82
	1b	27.1	2.58	0.82
	1c	41.1	3.68	0.82
	1d	27.4	2.51	0.82
	1e	21.7	2.23	0.82
Tube	2a	51.1	4.13	1.06
	2b	68.7	5.00	1.06
Tube	3a	33.9	2.41	0.48
Tube	4a	22.1	2.29	0.83
	4b	35.8	2.81	0.83
	4c	43.1	3.66	0.83
	4d	60.4	5.33	0.83
Tube	5a	51.4	4.35	0.90
	5b	32.1	2.58	0.90
	5c	37.9	3.15	0.90

Table 4. Results of Trial T13L (bladder reservoir). Suction in PTPNDS = 2.0 cm H2O, PPF = 230 umol/m2/sec.

		Top gfw	Top gdw	Root gdw
Tube	1a	2.17	0.36	0.12
	1b	3.16	0.47	0.12
	1c	4.14	0.59	0.12
	1d	1.30	0.26	0.12
Tube	2a	10.87	1.34	0.31
	2b	6.74	0.89	0.31
	2c	4.09	0.62	0.31
Tube	3a	6.44	0.88	0.27
	3b	5.34	0.72	0.27
	3c	4.59	0.61	0.27
	3d	7.77	0.98	0.27
Tube	4a	2.01	0.27	0.26
	4b	10.20	1.09	0.26
	4c	6.34	0.75	0.26
Tube	5a	2.52	0.42	0.26
	5b	2.79	0.39	0.26
	5c	9.25	1.08	0.26
	5d	10.34	1.24	0.26

Table 5. Results of Trial T14L (open reservoir and bladder reservoir). Suction in PTPNDS = 4.0 cm H2O, PPF = 200 umol/m2/sec.

Open Reservoir (with standpipe)

		Top gfw	Top gdw	Root gdw
Tube	1as	34.9	2.73	0.79
	1bs	47.8	3.64	0.79
	1cs	26.8	2.56	0.79
Tube	2as	37.2	2.41	0.55
	2bs	37.6	2.44	0.55
	2cs	59.9	3.65	0.55
Tube	3as	57.0	3.97	0.67
	3bs	55.2	3.37	0.67
	3cs	50.4	3.62	0.67
Tube	4as	56.4	3.59	0.48
	4bs	59.9	4.07	0.48
	4cs	17.2	0.98	0.48
Tube	5as	33.2	2.21	0.70
	5bs	48.5	3.17	0.70
	5cs	61.1	4.76	0.70

....

Bladder Reservoir

		Top gfw	Top gdw	Root gdw
Tube	1ab	5.8	0.56	0.08
	1bb	10.8	1.67	0.08
	1cb	4.1	0.71	0.08
Tube	2ab	2.7	0.35	0.10
	2bb	7.4	1.07	0.10
Tube	3ab	16.3	2.07	0.14
	3bb	2.7	0.41	0.14
	3cb	7.8	1.29	0.14
Tube	4ab	11.9	1.62	0.20
	4bb	17.2	1.86	0.20
	4cb	4.5	0.51	0.20
Tube	5ab	9.3	0.92	0.11
	5bb	4.9	0.62	0.11
	5cb	2.7	0.35	0.11

Discussion: By comparison to growth rates reported it the literature, it appears that the control of solution to the lettuce roots through the membrane retards the growth rate approximately 2 days during a 28 day grow-out. At about 20 C, 65% RH, about 250 umol/s/m2 PPF and 700 ppm CO2, a plant of about 60 grams fresh weight can be produced under earth-normal gravity. Removal of the standpipe and closing the nutrient loop from the atmosphere appears to have a drastic effect on plant growth as shown in the final trial in which the suctions on the computer controlled system were set to about 4 cm H2O, which approximated the pressures on the bladder system. Dissolved oxygen in the bladder was about 4 ppm whereas it was measured to be about 7.5 ppm in the reservoir of the computer controlled system. Even though the pressures in both systems were about the same, there was much more condensation visible between the root containment flaps in the tubes on the computer control system which may indicate better water availability than in the bladder system. The primary problem encountered in these trials was seed germination and seedling establishment which probably accounts for the high variability observed, especially in the earlier trials.

Conclusions:

Under earth-normal gravity and lacking fine control of the suctions that control water availability, lettuce plants of up to 68 grams fresh weight were produced under the given environmental conditions. This is approximately a 2 day retardation in growth over the 28-day cycle in comparison to conventional hydroponic systems.

Spacing on the 0.75 m ceramic tubes should be about 0.25 m per plant for a 28-day cycle.

Earth normal gravity and/or reduced dissolved oxygen produced a drastic reduction in lettuce growth rate in the atmospherically closed bladder-reservoir system. If the lack of a stand-pipe is the primary cause of the reduction in growth, this problem will probably not exist under microgravity.

POROUS TUBE TRIAL T15S

Investigator(s): T. W. Dreschel Date: 23 DEC 89

Species (crop)/Cultivar: *Glycine max* cv. McCall

Env. Conditions: Temp.: 26/22 C RH: 55% PPF: 200

Photoperiod: 12/12 CO_2: ambient Other: 5 tubes, one at each of: 0.8, 0.6, 0.5, 0.4, and 0.1 (leaking) nutrient suction.

Experiment Objectives: Investigate the potential of growing soybeans on the porous tube system (ceramic) and determine if there is any suction effects from 0.1 (freely leaking) to 0.8 kPa. Two plants were placed on each tube following a 72 H period of germination in wet kimwipes. The nutrient solution used is the KSC-CELSS soybean hydroponic solution (Mackowiak, personal communication) and the environmental conditions and nutrient solutions variables were monitored with a PC and Optiware data logging system. Nutrient suction was monitored and controlled with this system (Thurston and Godfrey, unpublished). Plants were maintained for 85 days with flowering and pod initiation occurring at about day 30. By day 85, nearly all leaves had fallen from the plants, and were gathered up and dried and weighed. Thus, it is assumed that each plant produced one-tenth of the leaves collected.

Results: The following table reports the total biomass produced on each tube (two plants) as leaves and roots could not be separated.

Table 1. The results (gdw) of Trial T15S.

Tube #	Shoot	Root	Pod	Seed	Total	Suction (kPa)
1	17.87	4.75	12.02	29.31	63.95	0.8
2	15.74	3.85	11.70	26.78	58.07	0.6
3	16.87	2.39	7.21	17.83	44.30	0.5
4	17.39	3.14	12.36	27.81	60.70	0.4
5	18.62	2.17	10.86	25.65	57.30	0.1 (leaking)

Conclusions/Comments:

Within the range of suction in which these units were controlled, there does not appear to be a significant difference, even in the units where the solution was allowed to "freely" leak out to the roots and drain back to the reservoir. The per plant production is somewhat low (C. M. Mackowiak, R. M. Wheeler, personal communication) and this may be related to another factor besides suction (root restriction, oxygen limitation, etc.) or factors other than nutrient delivery technique, such as lighting, photoperiod, temperature, air flow, CO_2, etc. Throughout the growout the system functioned well and was successful in supporting the growth of soybeans for 85 days from seed, through flowering and seed set, and to harvest.

POROUS TUBE TRIAL T16T

Investigator(s): T. W. Dreschel   Date: 9/MAY/90

Species/Cultivar: *Lycopersicon esculentum* cv. Florida petite

Env. Conditions: Temp.: 23 C RH: 60% PPF: 200 umol/s/m2

Photoperiod: 12h/12h   CO2: 425 ppm   Other:

Experiment Objective and Methods: To test whether dwarf, cherry tomato plants will grow, flower and set fruit within the constraints of the porous (ceramic) tube system and to test whether changing the root wrap material or configuration will improve plant growth by allowing greater aeration of the rhizosphere wrap; #2 used a porous, hydrophobic wrap to allow gas exchange with atmosphere; #3 used spacers to provide a grater "free space: for root growth; #4 and #5 used the conventional root wrap. Tubes 1 through 4 were maintained with a suction of 0.4 kPa, tube 5 was allowed to leak by gravity.

Results: Two plants were maintained on each 75 cm tube, placed alternately to avoid shading by surrounding plants as much as possible. Solution was maintained by adding 1/2 strength KSC CELSS hydroponic solution to the reservoir and the pH was adjusted to 6.0 with 2% HNO3 as needed. The plants flowered at about 30 days and visible fruit was observed on day 47. The plants are numbered as to the tube (1 through 5) and position on the tube (V = valve end of tube, P = pump end of tube). Plant 1V wilted and died for no apparent reason at 50 days and was removed. Plants 2V and 2P were smaller than the other plants from the start and were wilted and dead at 80 days having set only a small amount of fruit (Table 1). The first harvest of fruit was on day 72 and the trail was terminated on day 92. Table 1 is a summary of the fruit numbers and fresh weights from each plant and Table 2 presents the shoot and root dry weights for each plant that survived until day 92.

Conclusions/Comments:

It appears from this trial that:

- The hydrophobic, porous wrap allowed excessive drying of the rhizosphere. Thus at a time when the plants were filling fruit and probably required more water, there was no insufficient water available to sustain them.

- One plant on tube #1 produced more fruit than two under similar conditions on tube #4. This indicates that there may have been a growth limitation due to competition for root-surface area contact on the porous tube. This is not clear-cut though, as there was probably some shading effect on the #4 plants.

- The spacers on tube #3 had no beneficial effect on fruit production. This again was probably due to some drying of the rhizosphere as the fruit production was somewhat lower than in tube #4.

- Plants 5V and 5P did better than those maintained on a tube under suction with the exception of the single plant on tube #1 which probably indicated the benefits of extra lighting from the sides for those plants or may indicate water stress in the others.

- The mean fruit weight for the single plants #1P was more than double that for most of the other plants and nearly so for #3V and #5V.

- The order of success (total fruit number and weigh) was:

  1. Two plants on a freely leaking tube/standard root wrap
  2. Single plant per tube under suction/standard root wrap
  3. Two plants per tube under suction/standard root wrap
  4. Two plants per tube under suction/with spacers inside standard root wrap
  5. Two plants per tube under suction/porous, hydrophobic root wrap

....

Table 1. The results of Trial T16T (fruit weight).

Plant no.	N	$\bar{X}$ (gfw)	S	Total (gfw)
1V	0	----	---	-----
1P	32	17.5	6.7	559.3
2V	12	3.2	2.3	38.0
2P	2	2.1	0.3	4.2
3V	13	9.5	4.4	123.1
3P	21	5.8	1.9	121.4
4V	21	6.3	2.7	131.9
4P	50	4.4	3.1	219.0
5V	60	9.9	3.8	595.4
5P	45	8.0	2.7	359.1

....

Table 2. The results of Trial T16T (harvested plants).

Plant no.	Shoot (gdw)	Root (gdw)	Root/Shoot
1V	----	----	
1P	26.9	2.9*	9.3*
2V	----	0.15	
2P	----	0.15	
3V	7.7	0.35	22.0
3P	7.7	0.35	22.0
4V	8.6	0.9	9.6
4P	14.9	0.9	16.6
5V	26.9	1.4	19.21
5P	16.7	1.4	11.93

*Includes the root produced by plant 1V prior to its removal.

POROUS TUBE TRIAL T17R

Investigator (s): T. W. Dreschel   Date: 13/September/91

Species (crop)/Cultivar: *Raphanus sativus* cv. Cherry Belle (CB), Giant White Globe (GWG), Early Scarlet Globe (ESG).

Env. Conditions: Temp.: 25-28 C RH: 35-60% PPF: 250 umol/s/m2

Photoperiod: continuous   CO2: ambient   Other: ambient

Experiment Objective: To determine whether radish plants can be grown on the porous tube system and produce expanded roots.

Results: In this 21-day trial, the radishes produced bulbs averaging 4.1 to 9.6 grams in size. Seven radish plants were grown on each 28 inch long porous tube unit. The resulting fresh weight means are presented as Table 1.

Conclusions/Comments: Radish plants grown for 21 days on the porous (ceramic) tube system did quite well and produced normal appearing storage roots on the upper surface of the tube, exposed to the air, between the flaps on black/white plastic that covers the root mat. This trial indicated that the porous tube nutrient delivery system can be used for growing radishes.

....

Table 1. Mean fresh weights (in grams) of radish plants grown on the porous tube system. Each value is the mean of seven plants.

Tube #	Variety	Tops	Storage Root	Fibrous Roots
1	GWG	5.7	5.4	4.4
2	CB	4.2	9.6	1.0
3	ESG	3.4	4.1	1.7
4	GWG	5.9	4.4	4.8
5	CB	5.7	4.6	1.1

POROUS TUBE TRIAL T18R-T20R

Investigator(s): T. W. Dreschel Date: 11/91

Species (crop)/Cultivar: *Raphanus sativus* cv. Red Prince.

Env. Conditions: Temp.: 25-28 C RH: 35-60% PPF: 250 umol/s/m2

Photoperiod: continuous CO2: ambient Other: ambient

Experiment Objective: To determine whether radish plants can be grown on the porous tube system with a bladder reservoir, membrane aeration system (artificial lung), automatic nutrient solution addition and produce expanded roots in multiple crops on the "same solution".

Results: In the first trial (22 days), single storage roots of up to 7.75 g fresh weight were obtained. In the second trial (23 days) single storage roots of up to 18.4 g fresh weight were obtained. In the third trial (26 days), single storage roots of up to 20.2 g fresh weight, but a number of the plants had begun to bolt (produce flowers).

Conclusions/Comments: Consecutive crops on the bladder reservoir system grown on the same (on demand replenishment) nutrient solution showed no evident ill effects. The variation within a tube and within a trial was quite large, possibly due to some shading of adjacent plants and variations in germination rate. The nutrient solution in the bladder at harvest exhibited no apparent increase in turbidity or indications of excessive fungal or bacterial growth. It appears that the ideal harvest date would be between 21 and 23 days which would be just prior to the plants beginning to bolt.

Table 1. Mean fresh weights/standard deviations (grams) of radish plants from trials T18R, T19R, and T20R.

Trial#	Days	Tube	N	Tops	Storage Root (gfw)	Fibrous Root (gfw)
T18R	21	1	9	5.1/1.1	3.8/1.8	1.9/nm*
T18R	21	2	11	4.4/1.1	4.3/2.0	1.7/nm
T18R	21	3	9	5.4/1.6	4.1/2.7	1.8/nm
T18R	21	4	7	6.5/1.7	5.4/3.5	2.0/nm
T18R	21	5	12	4.6/0.5	2.1/1.3	1.6/nm

*nm = not measured.

Trial#	Days	Tube	N	Tops	Storage Root (gfw)	Fibrous Root (gfw)
T19R	23	1	11	5.6/1.8	5.7/5.1	1.7/nm
T19R	23	2	12	5.1/1.1	7.3/4.7	1.7/nm
T19R	23	3	11	5.7/1.7	6.9/3.2	2.3/nm
T19R	23	4	12	6.2/2.1	5.7/5.0	1.9/nm
T19R	23	5	10	5.4/1.6	6.0/3.7	1.6/nm

Trial#	Days	Tube	N	Tops	Storage Root (gfw)	Fibrous Root (gfw)
T20R	26	1	7	7.9/2.6	9.5/4.7	2.5/nm
T20R	26	2	8	8.4/3.3	6.0/5.9	2.0/nm
T20R	26	3	9	6.2/2.8	8.5/6.7	1.6/nm
T20R	26	4	10	7.1/3.1	8.1/5.7	1.5/nm
T20R	26	5	9	6.2/2.6	6.0/4.3	1.9/nm

BIBLIOGRAPHY

Wright, B. D. and W. C. Bausch. 1984. A plant growth system for orbital plant experiments. Paper #84-2524 presented to the American Society of Agricultural Engineers.

Dreschel, T. W., R. P. Prince, C. R. Hinkle, and W. M. Knott, III. 1986. Tubular membrane plant growth unit for hydroponics in microgravity. Paper presented to the American Society for Gravitational and Space Biology.

Dreschel, T. W. 1986. An improved plant nutrient delivery system for microgravity. New Technology Report #KSC-11375, The National Aeronautics and Space Administration, J. F. Kennedy Space Center, Florida.

Dreschel, T. W., C. R. Hinkle, W. M. Knott, R. P. Prince, and J. C. Sager. 1987. Development of a membrane nutrient system. Presentation to the Space Life Sciences Symposium.

Dreschel, T. W., R. P. Prince, C. R. Hinkle, and W. M. Knott. 1987. Porous membrane utilization in plant nutrient delivery. Paper #87-4025 presented to the American Society of Agricultural Engineers.

Bubenheim, D. L., T. W. Dreschel, and C. A. Mitchell. 1987. Comparison of plant growth in a tubular membrane hydroponic system with that in conventional hydroponic culture. HortScience 22(5): 75 (abstr).

Dreschel, T. W. 1987. Pressure monitoring and control system for the Tubular Membrane Plant Growth Unit. New Technology Report #KSC-11416, The National Aeronautics and Space Administration, J. F. Kennedy Space Center, Florida.

Dreschel, T. W., J. C. Sager, and R. M. Wheeler. 1988. Status of porous tube plant growth unit research. Paper #88-4524 presented to the American Society of Agricultural Engineers.

Wright, B. D., W. C. Bausch, and W. M. Knott. 1988. A hydroponic system for microgravity plant experiments. Trans. ASAE 31:440-446.

Dreschel, T. W., J. C. Sager, and R. M. Wheeler. 1989. Plant growth in a porous tube nutrient delivery system: The effects of pressure and pore size on productivity. ASGSB Bulletin 2(1): 37-38 (abstr).

Dreschel, T. W. and J. C. Sager. 1989. Control of water and nutrients using a porous tube: A method for growing plants in space. HortScience 24(6):944-947.

Dreschel, T. W., R. M. Wheeler, J. C. Sager, and W. M. Knott. 1989. Factors affecting plant growth in membrane nutrient delivery. In R. D. MacElroy, ed. Controlled Ecological Life Support Systems: CELSS '89 Workshop, NASA Technical Memorandum #102277, Ames Research Center, Moffett Field, California.

Peterson, T. A., D. T. Krizek, and T. W. Dreschel. 1989. Tomato plant growth on a CELSS tubular membrane growth unit. ASGSB Bulletin 3(1): 93 (abstr).

Dreschel, T. W. and C. S. Brown. 1990. Porous tube plant nutrient delivery system for the Space Shuttle mid-deck locker Plant Growth Unit (PGU). NASA New Technology Report #KSC-11536.

Dreschel, T. W., C. S. Brown, C. R. Hinkle, J. C. Sager, and W. M. Knott. 1990. Developing future plant experiments for spaceflight. Paper #90-4533 presented at the American Society of Agricultural Engineers Winter Meeting.

Dreschel, T. 1990. Plant Nutrient Delivery System having a Porous Tubular Member. Patent # 4,926,585. United States Patent and Trademark Office, Washington, D. C.

Dreschel, T. W., C. S. Brown, C. R. Hinkle, J. C. Sager, and W. M. Knott. 1990. Development of a porous tube plant nutrient delivery system for the Space Shuttle mid-deck locker Plant Growth Unit. ASGSB Bulletin 4(1): 51 (abstr).

Dreschel, T. W., C. S. Brown, W. C. Piastuch, R. M. Wheeler, and W.M. Knott. 1991. Technologies for plant space biology investigations in the Space Shuttle mid-deck locker. ASGSB Bulletin 5(1): 90 (abstr).

Takahashi, H., C. S. Brown, T. W. Dreschel, and T. K. Scott. 1991. Root hydrotropism in a porous tube water delivering system. ASGSB Bulletin 5(1): 46 (abstr).

Berry, W. L., G. Goldstein, T. W. Dreschel, R. M. Wheeler, J. C. Sager, and W. M. Knott. 1992. Water relations, gas exchange, and nutrient response to a long term constant water deficit. Soil Science (in press).

Dreschel, T. W. 1992. Hydroponics. Manuscript accepted for publication in the McGraw-Hill Encyclopedia of Science and Technology, Seventh Edition, Volume 8, p 607-610.

Takahashi, H., C. S. Brown, T. W. Dreschel, and T. K. Scott. 1992. Root hydrotropism in a porous tube water delivering system. HortScience (in press).

Tsao, D., M. R. Okos, J. C. Sager, and T. W. Dreschel. 1992. Development of physical and mathematical models for the porous ceramic tube plant nutrification system (PCTPNS). NASA Technical Memorandum (in preparation).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
JAN. 1992

3. REPORT TYPE AND DATES COVERED
NASA Technical Memorandum

4. TITLE AND SUBTITLE
A Summary of Porous Tube Plant Nutrient Delivery System Investigations From 1985 to 1991

5. FUNDING NUMBERS
NAS10-11624

6. AUTHOR(S)
T.W. Dreschel, C.S. Brown, W.C. Piastuch, C.R. Hinkle, *J.C. Sager, *R.M. Wheeler, and *W.M. Knott

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Bionetics Corporation
Mail Code: BIO-1
Kennedy Space Center, FL 32899

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
*Biomedical Operations and Research Office
Mail Code: MD
Kennedy Space Center, FL 32899

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TM 107546

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Publicly Available

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Porous Tube Plant Nutrient Delivery System (PTPNDS) has been developed for the Controlled Ecological Life Support System and the Plant Space Biology programs. The PTPNDS utilizes hydrophilic, microporous material tubes to control water and nutrient delivery to plant roots by capillary action. It has been designed and analyzed to support plant growth independent of gravity and plans are progressing to test it in microgravity. It has been used successfully to grow food crops to maturity in an earth-bound laboratory. This document includes a bibliography and summary reports from many of the growth trials performed at Kennedy Space Center utilizing the PTPNDS.

14. SUBJECT TERMS
Plants, Nutrient Delivery, Life Support

15. NUMBER OF PAGES
37

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified			