A Biologically-Based Alternative Water Processor for Long Duration Space Missions

Daniel J. Barta, Ph.D., Karen D. Pickering, Ph.D., Caitlin Meyer, Stuart Pensinger, Leticia Vega
NASA Johnson Space Center, Houston, Texas

Michael Flynn
NASA Ames Research Center, Moffet Field, California

Andrew Jackson, Ph.D.
Texas Tech University, Lubbock, Texas

Raymond Wheeler
NASA Kennedy Space Center, Florida

A wastewater recovery system has been developed that combines novel biological and physicochemical components for recycling wastewater on long duration space missions. Functionally, this Alternative Water Processor (AWP) would replace the Urine Processing Assembly on the International Space Station and reduce or eliminate the need for the multi-filtration beds of the Water Processing Assembly (WPA). At its center are two unique game changing technologies: 1) a biological water processor (BWP) to mineralize organic forms of carbon and nitrogen and 2) an advanced membrane processor (Forward Osmosis Secondary Treatment) for removal of solids and inorganic ions. The AWP is designed for recycling larger quantities of wastewater from multiple sources expected during future exploration missions, including urine, hygiene (hand wash, shower, oral and shave) and laundry. The BWP utilizes a single-stage membrane-aerated biological reactor for simultaneous nitrification and denitrification. The Forward Osmosis Secondary Treatment (FOST) system uses a combination of forward osmosis (FO) and reverse osmosis (RO), is resistant to biofouling and can easily tolerate wastewaters high in non-volatile organics and solids associated with shower and/or hand washing. The BWP was operated continuously for over 300 days. After startup, the mature biological system averaged 85% organic carbon removal and 44% nitrogen removal, close to maximum based on available carbon. The FOST has averaged 93% water recovery, with a maximum of 98%. If the wastewater is slighty acidified, ammonia rejection is optimal. This paper will provide a description of the technology and summarize results from ground-based testing using real wastewater.

National Aeronautics and Space Administration

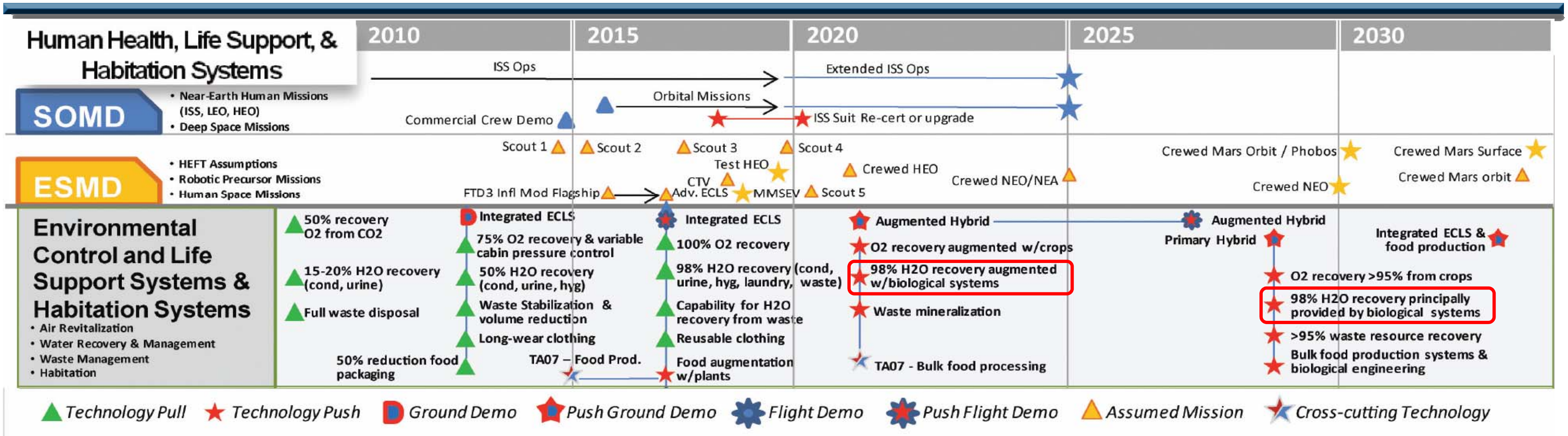
A Biologically-Based Alternative Water Processor for Long Duration Space Missions

Daniel J. Barta, Ph.D.
NASA Johnson Space Center, Houston, TX, USA

Co-Authors:
Karen D. Pickering, Ph.D., Caitlin Meyer, Stuart Pensinger, Leticia Vega, *NASA Johnson Space Center*
Michael Flynn, *NASA Ames Research Center*
Andrew Jackson, *Texas Tech University, Lubbock, TX*
Raymond Wheeler, *NASA Kennedy Space Center*

18-19 May, 2015
ISLSWG BLS Workshop

2012 NASA Space Technology Roadmap Technology Area 06
Human Health, Life Support and Habitation Systems*



State of the Art	Major Challenges	Milestones to Advance TRL
International Space Station Water Recovery System Recovers H_2O from only humidity condensate and urine which is only 15-20% of the anticipated wastewater load for exploration missions	• Attain high reliability • Reduce utilization of expendables • Reduce power and equipment mass and volume • Reduce acoustic emissions • Recover water from additional sources, including hygiene and laundry • Increase overall water recovery percentage • Stabilize wastewater from multiple sources in manners that are compatible with processing systems • Disinfect and maintain microbial control of potable water	**2011-14:** 40-55% H_2O recovery (condensate, urine, hygiene) **2015-19:** 98% H_2O recovery (condensate, urine, hygiene, laundry, waste) **2020-24:** 98% H_2O recovery augmented by biological systems (condensate, urine, hygiene, laundry, waste, In-Situ Resource Utilization (ISRU)-derived) **2025-29:** 98% H_2O recovery principally provided by biological systems

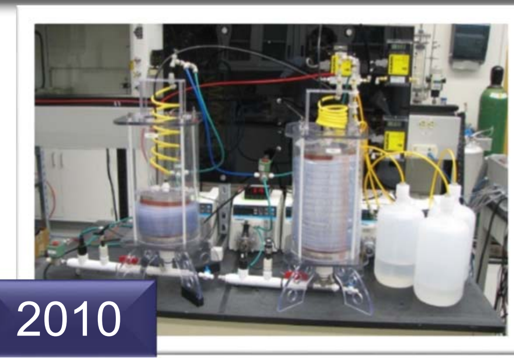
*Draft updates for 2015 were recently released: http://www.nasa.gov/offices/oct/home/roadmaps/index.html

Examples of NASA-Sponsored Biological Water Processor technology Development


1997

Verostko, C., M. Edeen, N. Packham, 1992. “A Hybrid Regenerative Water Recovery System for Lunar/Mars Life Support Applications," SAE Technical Paper 921276

Pickering, K. and Edeen, M., 1998. "Lunar-Mars Life Support Test Project Phase III Water Recovery System Operation and Results," SAE Technical Paper 981707


2010

Bellows Bioreactors


2006

Rector, T., J. Garland, K. Reid-Black, R.F. Strayer, M. Hummerick, M. Roberts, and L. Levine. 2006. Treatment of an early planetary base waste stream in a rotating hollow fiber membrane reactor. Earth and Space. 188:45-51.


2002

Pickering, K., G. Pariani, B. Finger, M. Campbell; J. Gandhi, C. Carrier and L. Vega. 2001. Testing of a Microgravity-Compatible Biological Water Processor System. 31st International Conference on Environmental Systems, Orlando, FL

M. Campbell, B. Finger, C. Verostko, K. Wines, G. Pariani, K. Pickering. 2003. Integrated Water Recovery System Test. SAE Paper 2003-01-2577.


2011

Jackson, W.A., D. Christenson, K. Kubista, A. Morse, S. Morse, T. Vercellino, D. Wilson, and J.L. Garland. 2011. Performance of a TRL 5 bioreactor for pretreatment of an extended habitation waste stream. Amer. Inst. Aeronautics Astronautics, AIAA-2011-5132, 41st ICES, Portland, Oregon.

Alternative Water Processor
Overview

Biological Water Processor

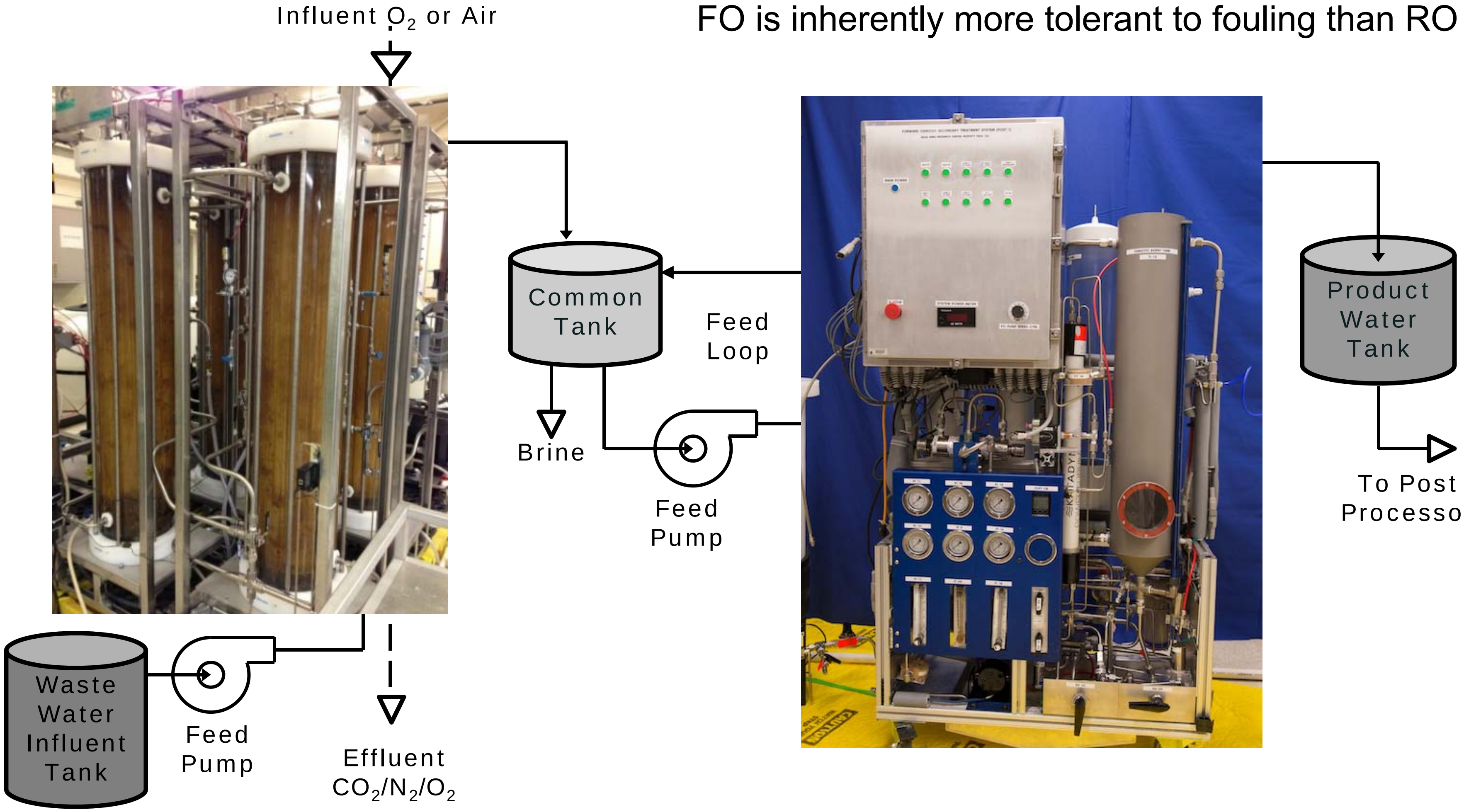
4 Membrane Aerated Biological Reactors

Mineralization of organic carbon & nitrogen

Forward Osmosis Secondary Treatment System

Function: mineral salt and solids removal

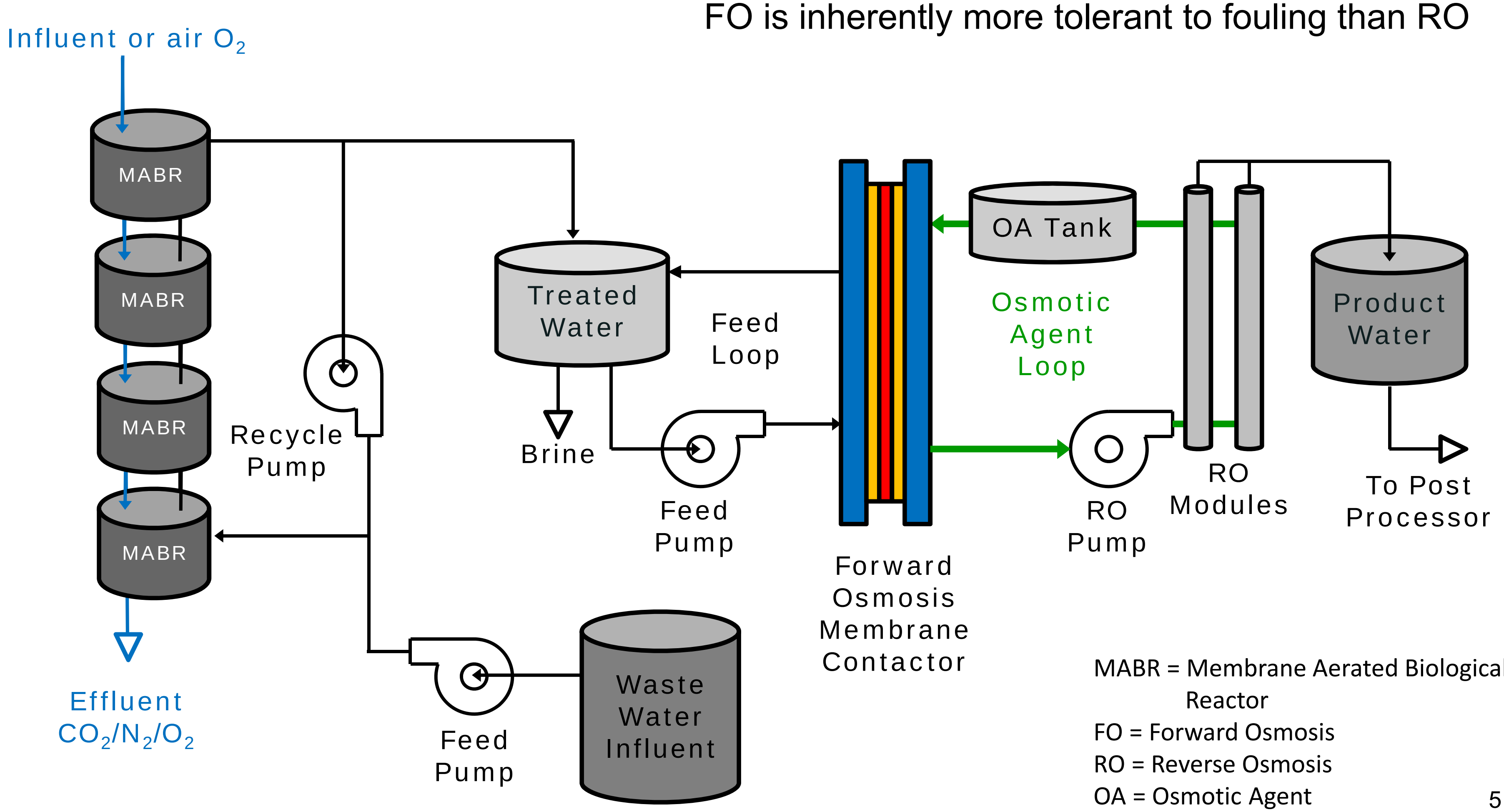
FO is inherently more tolerant to fouling than RO



Alternative Water Processor
Overview

Biological Water Processor
4 Membrane Aerated Biological Reactors
Mineralization of organic carbon & nitrogen

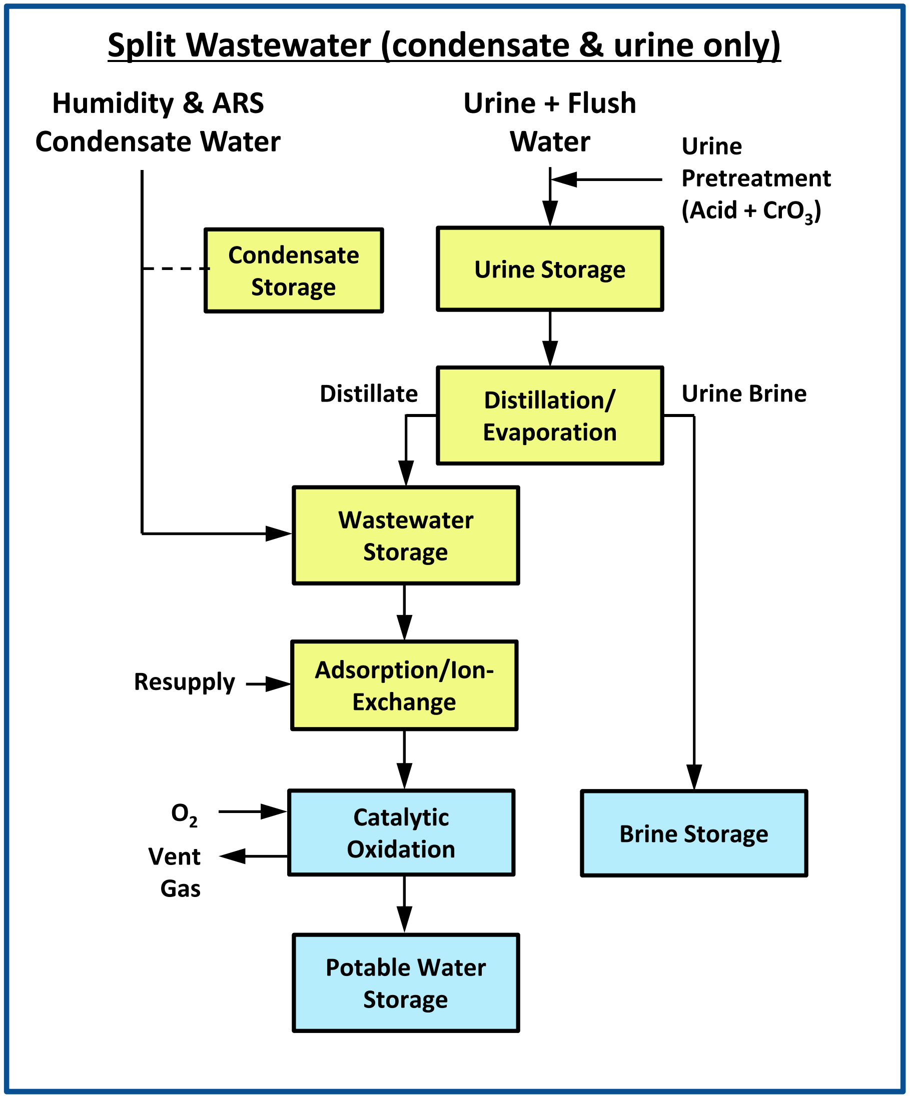
Forward Osmosis Secondary Treatment System
Function: mineral salt and solids removal
FO is inherently more tolerant to fouling than RO



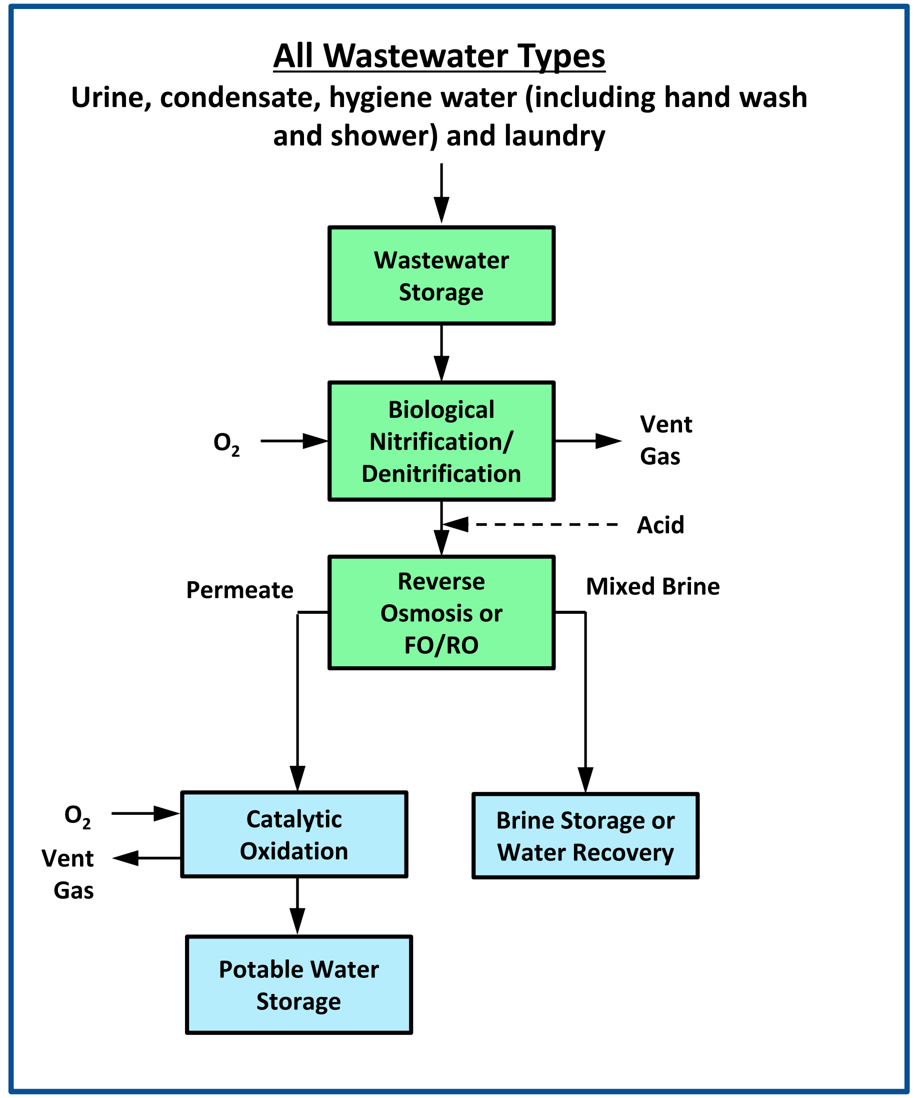
MABR = Membrane Aerated Biological Reactor
FO = Forward Osmosis
RO = Reverse Osmosis
OA = Osmotic Agent

Water Recovery System Architectures

International Space Station (ISS)



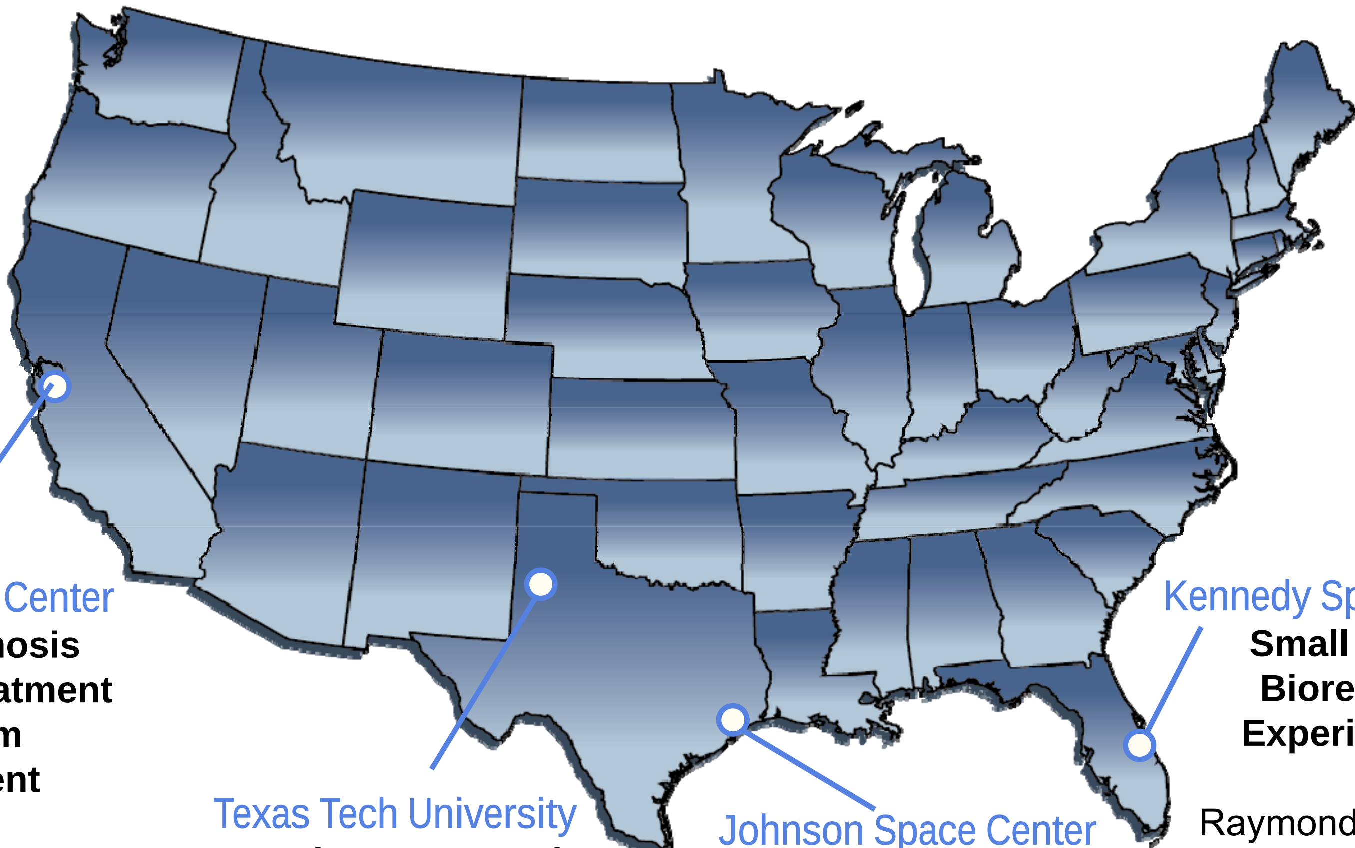
Alternative Water Processor



ARS = Atmosphere Revitalization System (CO_2 Reduction); FO/RO = Forward Osmosis/Reverse Osmosis

Common	ISS Unique	AWP Unique

A Collaborative Approach



Ames Research Center

Forward Osmosis Secondary Treatment Subsystem Development

Michael Flynn
Tra-My Justine Richardson
Enid Contés-de Jesús
Hali Shaw
Jurek Parodi

Texas Tech University

Membrane Aerated Bioreactor Design & Evaluation

W. Andrew Jackson
Dylan Christenson
Audra Morse

Johnson Space Center

Integrated System Testing

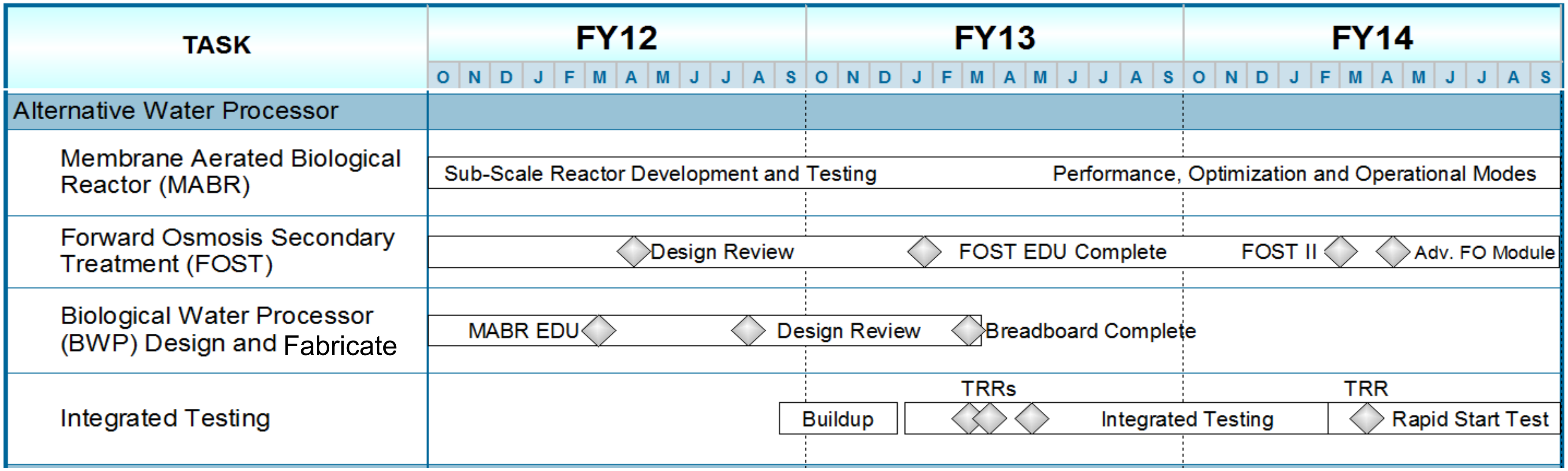
Karen Pickering
Caitlin Meyer
Leticia Vega
Stuart Pensinger

Kennedy Space Center

Small Scale Bioreactor Experiments

Raymond Wheeler
Griffin Lunn
Janelle Coutts
Anna Maria Ruby
Michele Birmele
Michael Roberts

Alternative Water Processor
Schedule and Developmental Sequence



- This presentation focuses on tasks from Fiscal Year 2012 to mid-2014, through the end of the first phase of integrated testing.
- Tests performed in the later part of 2014 will be presented at the 2015 International Conference on Environmental Systems, Bellevue, WA, USA

  Meyer, C., S. Pensinger, K. Pickering, D. Barta , S. Shull, L. Vega, D. Christenson and W. A. Jackson. 2015. Rapid Start-up and Loading of an Attached Growth, Simultaneous Nitrification/ Denitrification Membrane Aerated Bioreactor. ICES-2015-210.

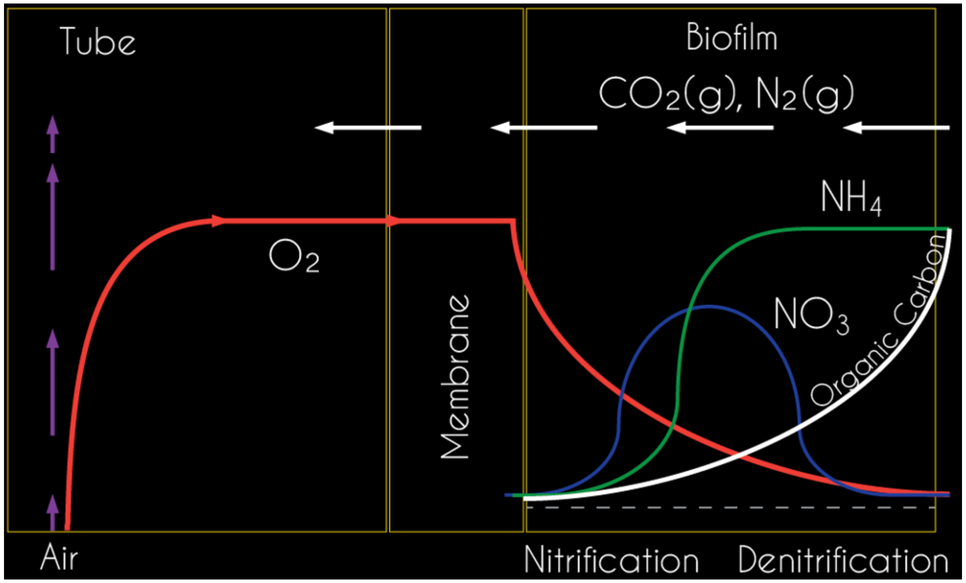
  Hummerick, M.E., J.L. Coutts, G. M. Lunn , L. Spencer , C.L. Khodadad, S. Frances, and R. Wheeler. 2015. Dormancy and recovery testing for biological wastewater processors. ICES Paper 2015-197

- Work continues in Fiscal Year 2015
  - o Determine composition of the microbial community within a bioreactor
  - o Determine optimum geometry for flight hardware system
  - o Determine the influence of additional carbon producers (i.e. increased C:N) on bioreactor performance and effluent quality

Alternative Water Processor Subsystems
Biological Water Processor (BWP)

- Based on Membrane Aerated Biological Reactor (MABR) technology from Texas Tech University.
- Oxygen or air flows within the lumen of silastic tubing, separating it from the aqueous phase containing wastewater.
- Biofilm grows on outer surface of tubing.
- This single-stage system performs carbon oxidation & simultaneous nitrification & denitrification, mineralizing organic carbon and nitrogen.
- Co-diffusion: oxygen diffuses into the reactor and nitrogen, carbon dioxide and other gases diffuse out.

- Each MABR was sized to treat at least 1-person's wastewater (as measured ≈2)
- Four MABRs were assembled together to make the Biological Water Processor (BWP)



Urea hydrolysis:

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2$$

Nitrification:

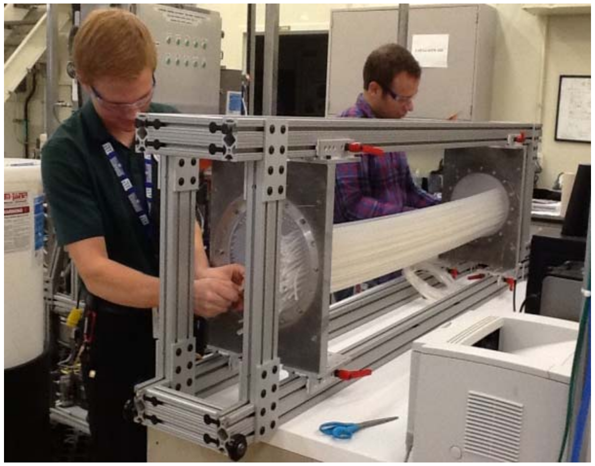
$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

Denitrification:

$$\text{Organic Carbon} + NO_3^- \rightarrow N_2 + HCO_3^- + H_2O$$

Membrane Aerated Biological Reactor (MABR)

Fabrication and Selected Bioreactor Parameters



Stringing Silastic tubing during fabrication, 506 tubes per module.

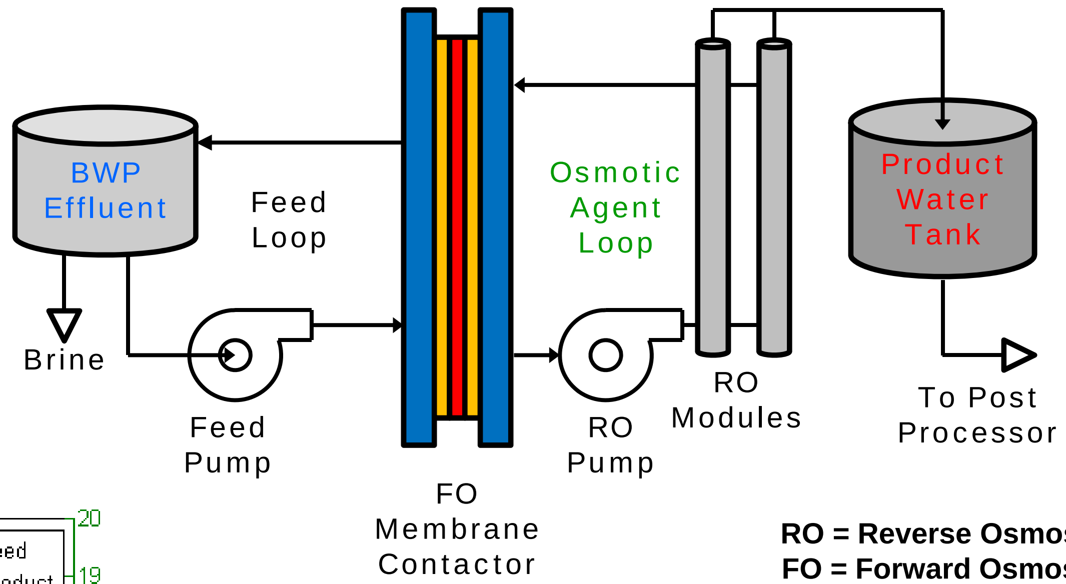
Newly assembled MABRs. The Forward Osmosis Secondary Treatment system is to the right

MABRs after extended operation

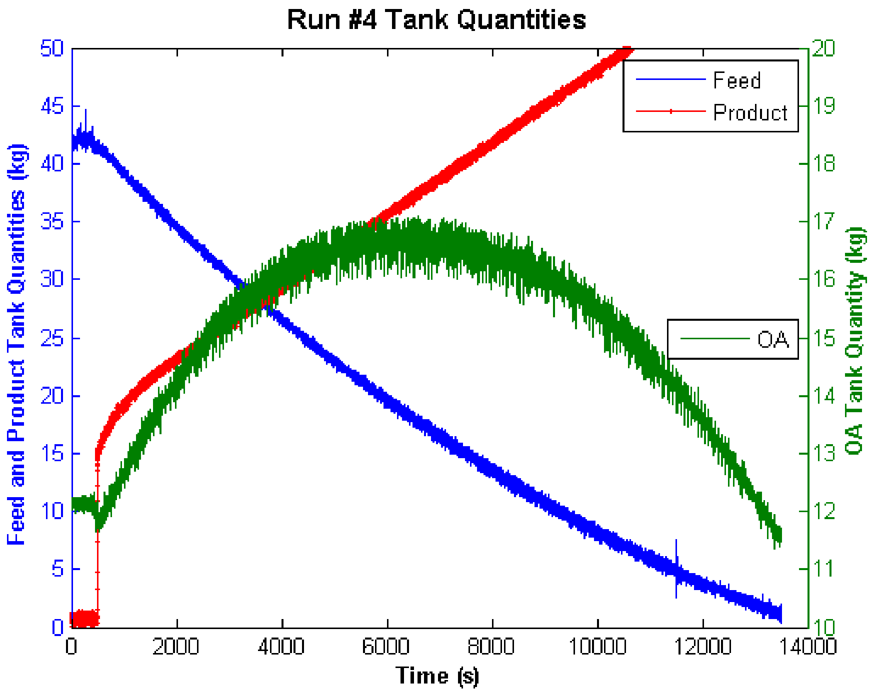
Parameter	Value	Units
Liquid Volume per Reactor	55	L
Membrane Surface Area per Reactor	11	m^2
Influent Wastewater Feed Rate	60	mL/min
Liquid Recycle Flow Rate	11.3	L/min
Daily Timing Feeding:Recycle	16:8	hr:hr
Hydraulic Retention Time (HRT)	2.0	days
Gas Flow Rate (air or oxygen)	0.5	L/min

Alternative Water Processor Components
Forward Osmosis Secondary Treatment (FOST)

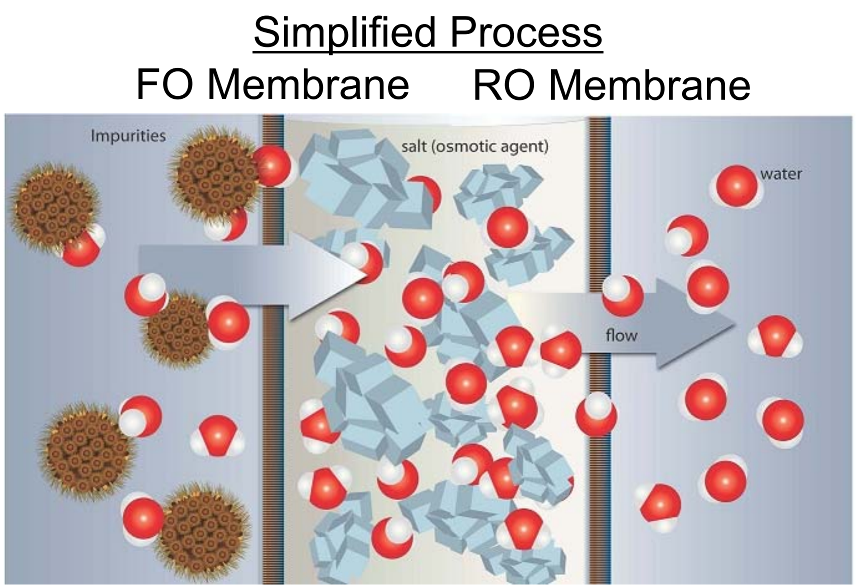
- Bioreactor effluent is recirculated across a Forward Osmosis (FO) membrane.
- Purified water is drawn through the membrane into an osmotic agent (NaCl), then extracted using an energy recuperative Reverse Osmosis (RO).



RO = Reverse Osmosis
FO = Forward Osmosis



Changes in FOST Tank Levels during a run



Integrated Testing

Wastewater Formulation & Loading

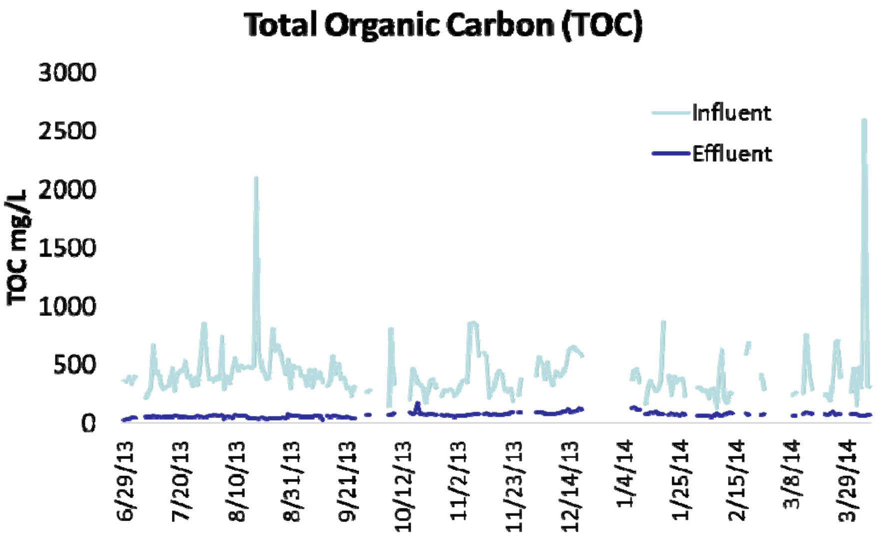
- "Exploration wastewater" was used, made up of humidity condensate and collected urine and urine flush, plus hygiene (hand wash, oral, shave and shower) and laundry.
- All wastewater was collected at a donation facility except humidity condensate, which was ersatz.
- *Urine concentration was increased to simulated flight urine by changing ratios of urine and humidity condensate.
  - The flight equivalent per day per person is 1.2 kg urine and 1.95 kg humidity condensate. We used 2.275 kg ground-based urine & 1.15 kg humidity condensate per person per day.
- Laundry was run and added only on alternate days.
- Total loading rate is approximately 43.9 kg/day w/o laundry, 72.9 kg/d with laundry

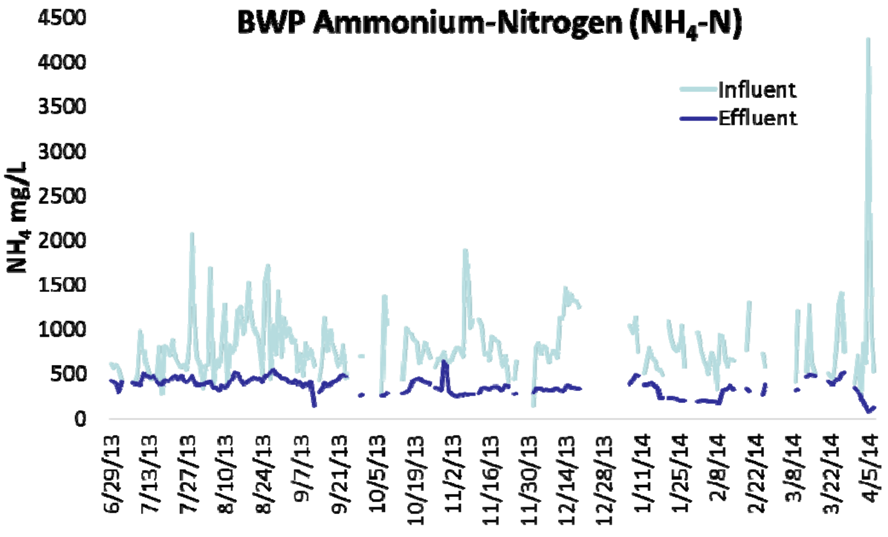
Parameter	Units	Ground Based Urine*	Humidity Condensate	Hygiene					Laundry
				Urinal Flush	Hand Wash	Shower	Shave	Oral	
Frequency of event	Events/4 crew/d				32	4	1	8	1 per 2 days
Amount per event	kg/event				0.125	6.0	0.15	0.1	28-30
Nominal load	kg/person/d	2.275	1.15	0.3	1.0	6.0	0.04	0.2	3.5-3.8
	kg/4 crew/d	9.1	4.6	1.2	4.0	24.0	0.15	0.8	14-15

Alternative Water Processor Integrated Test
Results - Biological Water Processor

Integrated Test

- The first phase of integrated testing (4 bioreactors) was initiated April 19, 2013 with BWP inoculation and ended April 8, 2014.
- Average conversion: 85% organic carbon & 55% ammonium.
- The BWP performed C and N removal to the maximum capacity of nutrients available in the wastewater composition.
  - The wastewater is carbon limited. Literature suggests a ratio between 3:1 and 5:1 for optimum denitrification. Our wastewater is ≈0.5:1.
- 2 of the 4 original bioreactors were operated continuously for a period of more than 500 days.



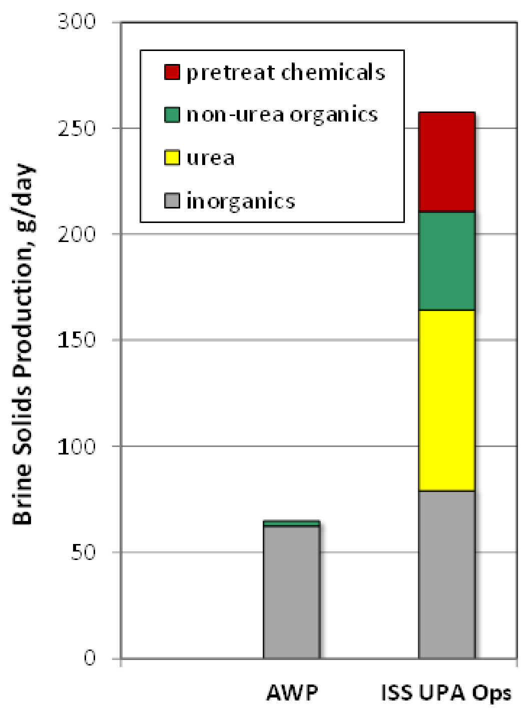


Alternative Water Processor Integrated Test

Results - Forward Osmosis Secondary Treatment Subsystem

Accomplishments / Findings

- Multiple test runs were performed using BWP effluent.
- Water recovery averaged 92%, with a maximum of 98%
- Acidification of bioreactor effluent is necessary to achieve acceptable product water (Runs #1-4)
- Total system consumables were calculated to be 29% lower than the ISS.
- Brines generated by the FOST have lower solids level making post treatment easier.



FOST Brine Solids compared to ISS Brine

FOST Product Water Quality						
	pH	TOC	Na^+	Cl^-	NH_4^+	SO_4^{2-}
		PPM				
SWEG	-	3	-	-	1	-
MPCV 70156	-	0.5	-	0.3	0.5	250
SSP 50260	5.5-9.0	-	-	250	2	250
Run A	9.21	<0.5	45	122	27	32
Run B	9.1	<0.5	70	114	64	1
Run C	9.4	<0.5	53	78	43	1.4
Run D	9.39	<0.5	49	81	62	1.2
Run #1	6.63	<0.5	28	62	<0.5	28
Run #2	6.45	1.1	34	94	<0.5	25
Run #3	5.01	1	29	83	<0.5	23
Run #4	4.81	0.92	46	71	0.6	<0.5

Alternative Water Processor
Supporting Research Investigations

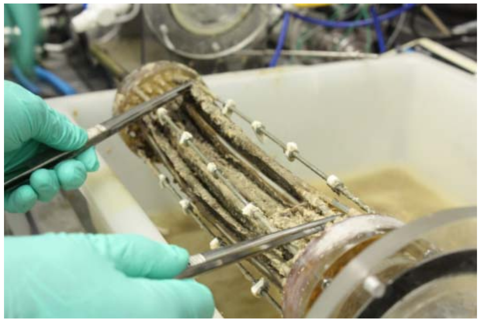
Texas Tech University

- A single full-scale biological reactor was used to investigate wastewater loading rates, oxygen/air flow and dormancy.

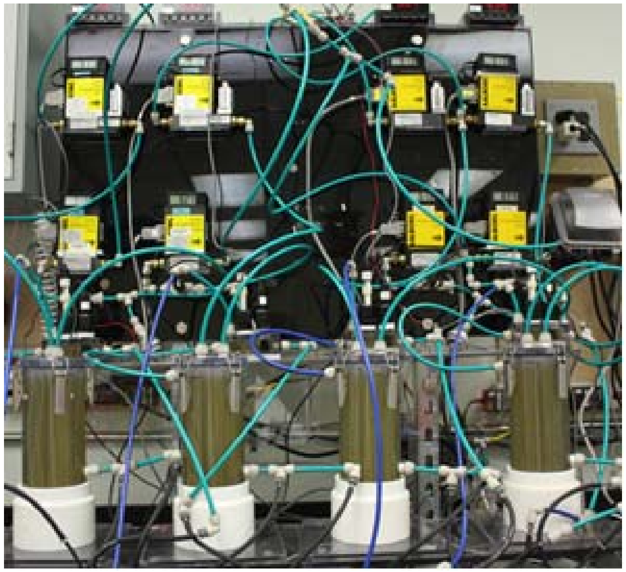
Counter-diffusion Membrane Aerated Nitrifying Denitrifying Reactor (CoMANDER) at Texas Tech University

Kennedy Space Center

- Small scale studies at KSC on methods to promote biofilm attachment led to a recommendation for use of a treatment to etch membrane fibers.
- Dormancy Studies demonstrated that at least for up to 4 weeks, a reactor can be put into recycle mode and can be brought back on line with no start up required.
- Microbial community characterization



Small scale reactors at KSC used to study biofilm attachment.



Dormancy Studies at KSC

Closing Remarks

Summary

- The Alternative Water Processor is a “green” choice for spacecraft water recycling, exploiting natural biodegradation processes to mineralize organic and nitrogen compounds in wastewater.
- The system is capable of treating a complex wastewater stream that includes urine, condensate, hygiene water (including hand wash and shower), and laundry.
- The system requires fewer consumables (chiefly salt & acid) than current flight systems (pretreatment chemicals & multi-filtration beds).
- The system was designed to be compatible with microgravity and/or partial gravity conditions.

Challenges

- Bio-fouling of fluid lines, pumps and sensors
- Methods for inoculation in flight
- Decreasing time to full biological activity following inoculation.
- Spacecraft quiescence and bioreactor dormancy.
- Improvement in salt rejection, rate of water permeance and life of forward and reverse osmosis membranes.
- Long life energy recuperative pumps for reverse osmosis
- Automated Systems Control