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 slightly acidified, ammonia rejection is optimal. This paper will provide a description of the technology and summarize results from ground-based testing using real wastewater.
A Biologically-Based Alternative Water Processor for Long Duration Space Missions

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International Space Station Water Recovery System

Recovers H₂O from only humidity condensate and urine which is only 15-20% of the anticipated wastewater load for exploration missions

**State of the Art**

**Major Challenges**

- 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

**Milestones to Advance TRL**

- **2011-14:** 40-55% H₂O recovery (condensate, urine, hygiene)
- **2015-19:** 98% H₂O recovery (condensate, urine, hygiene, laundry, waste)
- **2020-24:** 98% H₂O recovery augmented by biological systems (condensate, urine, hygiene, laundry, waste, In-Situ Resource Utilization (ISRU)-derived)
- **2025-29:** 98% H₂O recovery principally provided by biological systems
Examples of NASA-Sponsored Biological Water Processor technology Development


Alternative Water Processor
Overview

Biological Water Processor
4 Membrane Aerated Biological Reactors
Mineralization of organic carbon & nitrogen
Influent $O_2$ or Air

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

- Waste Water Influent Tank
- Feed Pump
- Effluent $CO_2/N_2/O_2$
- Common Tank
- Feed Loop
- Brine
- Feed Pump
- Product Water Tank
- To Post Processor
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)**

*Split Wastewater (condensate & urine only)*

- Humidity & ARS Condensate Water
  - Condensate Storage
  - Adsorption/Ion-Exchange
  - Wastewater Storage
  - Potable Water Storage
- Urine + Flush Water
  - Urine Pretreatment (Acid + CrO₃)
  - Distillation/Evaporation
  - Distillate
  - Urine Storage
- Urine Brine

**Alternative Water Processor**

*All Wastewater Types*

- Urine, condensate, hygiene water (including hand wash and shower) and laundry
- Wastewater Storage
- Biological Nitrification/Denitrification
  - O₂
  - Vent Gas
  - Acid
  - Permeate
  - Reverse Osmosis or FO/RO
  - Mixed Brine

*Common*
- Catalytic Oxidation
  - O₂
  - Vent Gas
  - Potable Water Storage
  - Brine Storage or Water Recovery

*ISS Unique*
- Common

*AWP Unique*
- Common

ARS = Atmosphere Revitalization System (CO₂ Reduction); FO/RO = Forward Osmosis/Reverse Osmosis
A Collaborative Approach

Kennedy Space Center
Small Scale Bioreactor Experiments
Raymond Wheeler
Griffin Lunn
Janelle Coutts
Anna Maria Ruby
Michele Birmele
Michael Roberts

Johnson Space Center
Integrated System Testing
Karen Pickering
Caitlin Meyer
Leticia Vega
Stuart Pensinger

Texas Tech University
Membrane Aerated Bioreactor Design & Evaluation
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Dylan Christenson
Audra Morse

Ames Research Center
Forward Osmosis Secondary Treatment Subsystem Development
Michael Flynn
Tra-My Justine Richardson
Enid Contés-de Jesús
Hali Shaw
Jurek Parodi

Kennedy Space Center
Small Scale Bioreactor Experiments
Raymond Wheeler
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Janelle Coutts
Anna Maria Ruby
Michele Birmele
Michael Roberts
Alternative Water Processor
Schedule and Developmental Sequence

<table>
<thead>
<tr>
<th>TASK</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
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<tbody>
<tr>
<td>Membrane Aerated Biological Reactor (MABR)</td>
<td>Sub-Scale Reactor Development and Testing</td>
<td>Performance, Optimization and Operational Modes</td>
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<tr>
<td>Forward Osmosis Secondary Treatment (FOST)</td>
<td>Design Review</td>
<td>FOST EDU Complete</td>
<td>FOST II Adv. FO Module</td>
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<tr>
<td>Biological Water Processor (BWP) Design and Fabricate</td>
<td>MABR EDU Design Review Breadboard Complete</td>
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<tr>
<td>Integrated Testing</td>
<td>TRRs Integrated Testing</td>
<td>TRR Rapid Start Test</td>
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- 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
- 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:**
\[ \text{CO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2 \]

**Nitrification:**
\[ \text{NH}_4^+ + 2\text{O}_2 \rightarrow \text{NO}_3^- + 2\text{H}^+ + \text{H}_2\text{O} \]

**Denitrification:**
\[ \text{Organic Carbon} + \text{NO}_3^- \rightarrow \text{N}_2 + \text{HCO}_3^- + \text{H}_2\text{O} \]
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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>Liquid Volume per Reactor</td>
<td>55</td>
<td>L</td>
</tr>
<tr>
<td>Membrane Surface Area per Reactor</td>
<td>11</td>
<td>m²</td>
</tr>
<tr>
<td>Influent Wastewater Feed Rate</td>
<td>60</td>
<td>mL/min</td>
</tr>
<tr>
<td>Liquid Recycle Flow Rate</td>
<td>11.3</td>
<td>L/min</td>
</tr>
<tr>
<td>Daily Timing Feeding:Recycle</td>
<td>16:8</td>
<td>hr:hr</td>
</tr>
<tr>
<td>Hydraulic Retention Time (HRT)</td>
<td>2.0</td>
<td>days</td>
</tr>
<tr>
<td>Gas Flow Rate (air or oxygen)</td>
<td>0.5</td>
<td>L/min</td>
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</table>
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).

Changes in FOST Tank Levels during a run

Run #4 Tank Quantities

Feed and Product Tank Quantities (kg)

Feed Pump

FO Membrane Contactor

RO Modules

Product Water Tank

To Post Processor

RO = Reverse Osmosis
FO = Forward Osmosis

Simplified Process

FO Membrane    RO Membrane

Impurities
salt (osmotic agent)

flow

water
### 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Ground Based Urine*</th>
<th>Humidity Condensate</th>
<th>Hygiene</th>
<th>Laundry</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Urinal Flush</td>
<td>Hand Wash</td>
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<tr>
<td>Frequency of event</td>
<td>Events/4 crew/d</td>
<td></td>
<td></td>
<td>32</td>
<td>4</td>
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<tr>
<td>Amount per event</td>
<td>kg/event</td>
<td></td>
<td></td>
<td>0.125</td>
<td>6.0</td>
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<tr>
<td>Nominal load</td>
<td>kg/person/d</td>
<td>2.275</td>
<td>1.15</td>
<td>0.3</td>
<td>1.0</td>
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<tr>
<td></td>
<td>kg/4 crew/d</td>
<td>9.1</td>
<td>4.6</td>
<td>1.2</td>
<td>4.0</td>
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</table>
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.
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 Product Water Quality

<table>
<thead>
<tr>
<th>Run</th>
<th>pH</th>
<th>TOC</th>
<th>Na⁺</th>
<th>Cl⁻</th>
<th>NH₄⁺</th>
<th>SO₄²⁻</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>PPM</td>
<td></td>
<td></td>
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<tr>
<td>SWEG</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
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<tr>
<td>MPCV 70156</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>0.3</td>
<td>0.5</td>
<td>250</td>
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<tr>
<td>SSP 50260</td>
<td>5.5-9.0</td>
<td>-</td>
<td>-</td>
<td>250</td>
<td>2</td>
<td>250</td>
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<tr>
<td>Run A</td>
<td>9.21</td>
<td>&lt;0.5</td>
<td>45</td>
<td>122</td>
<td>27</td>
<td>32</td>
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<tr>
<td>Run B</td>
<td>9.1</td>
<td>&lt;0.5</td>
<td>70</td>
<td>114</td>
<td>64</td>
<td>1</td>
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<tr>
<td>Run C</td>
<td>9.4</td>
<td>&lt;0.5</td>
<td>53</td>
<td>78</td>
<td>43</td>
<td>1.4</td>
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<tr>
<td>Run D</td>
<td>9.39</td>
<td>&lt;0.5</td>
<td>49</td>
<td>81</td>
<td>62</td>
<td>1.2</td>
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<tr>
<td>Run #1</td>
<td>6.63</td>
<td>&lt;0.5</td>
<td>28</td>
<td>62</td>
<td>&lt;0.5</td>
<td>28</td>
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<tr>
<td>Run #2</td>
<td>6.45</td>
<td>1.1</td>
<td>34</td>
<td>94</td>
<td>&lt;0.5</td>
<td>25</td>
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<tr>
<td>Run #3</td>
<td>5.01</td>
<td>1</td>
<td>29</td>
<td>83</td>
<td>&lt;0.5</td>
<td>23</td>
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<td>Run #4</td>
<td>4.81</td>
<td>0.92</td>
<td>46</td>
<td>71</td>
<td>0.6</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>

FOST Brine Solids compared to ISS Brine
Texas Tech University
• A single full-scale biological reactor was used to investigate wastewater loading rates, oxygen/air flow and dormancy.

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
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