Alternative Water Processor Test Development

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The Next Generation Life Support Project is developing an Alternative Water Processor (AWP) as a candidate water recovery system for long duration exploration missions. The AWP consists of biological water processor (BWP) integrated with a forward osmosis secondary treatment system (FOST). The basis of the BWP is a membrane aerated biological reactor (MABR), developed in concert with Texas Tech University. Bacteria located within the MABR metabolize organic material in wastewater, converting approximately 90% of the total organic carbon to carbon dioxide. In addition, bacteria convert a portion of the ammonia-nitrogen present in the wastewater to nitrogen gas, through a combination of nitrification and denitrification. The effluent from the BWP system is low in organic contaminants, but high in total dissolved solids. The FOST system, integrated downstream of the BWP, removes dissolved solids through a combination of concentration-driven forward osmosis and pressure driven reverse osmosis. The integrated system is expected to produce water with a total organic carbon less than 50 mg/l and dissolved solids that meet potable water requirements for spaceflight. This paper describes the test definition, the design of the BWP and FOST subsystems, and plans for integrated testing.

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I. Introduction

THE Alternative Water Processor (AWP) test is one of three tasks included in the Next Generation Life Support (NGLS) Project, with a goal to develop key technologies to enable critical capabilities for spacecraft life support systems needed to extend human presence beyond low Earth orbit.

The AWP effort will result in the development of a system capable of recycling wastewater from sources expected in future exploration missions, including hygiene and laundry water, using a "disruptive" technology based on natural biological processes. The AWP will be capable of recycling more than 95% of exploration wastewater, increasing closure compared to the state of the art. The performance of the AWP system will be quantified through systems-level testing, with delivery to the Advanced Exploration Systems Water Recovery Project when work is completed.

II. System Definition

The AWP system, located at Johnson Space Center in the Advanced Water Recovery System Development Facility (AWRSDF), is made up of a biological water processor (BWP), integrated with a forward osmosis ssecondary treatment system (FOST). The BWP utilizes bacteria for the oxidation of organic carbon and conversion of ammonium to produce carbon dioxide and nitrogen gas. It is anticipated that the BWP will oxidize at least 90% of the organic material present in the wastewater. Effluent from the BWP is expected to have total organic carbon concentrations less than 100 mg/l, however, the BWP will have little impact on the total inorganic dissolved solids in the wastewater. The effluent from the BWP will be treated by the FOST, which utilizes forward osmosis and reverse osmosis for removal of inorganic and residual organic contaminants. It is expected that the integrated system will recover 95% of the initial wastewater volume. The remaining 5% will be lost from the FOST as a concentrated brine stream. A simplied schematic of the integrated system is illustrated in Figure 1.

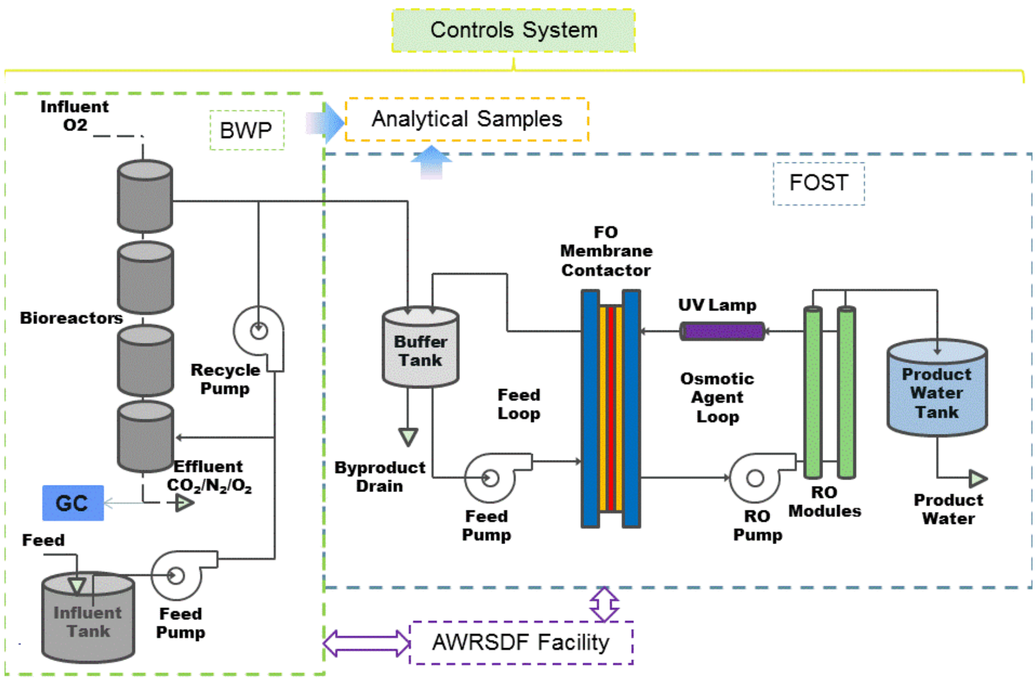

Figure 1. The alternative water processor integrated system.

A. Biological Water Processor

1. Principles of operation

The BWP subsystem is the primary water processor for the AWP, responsible for removing organic carbon and nitrogen from wastewater. The subsystem is made up of four Membrane Aerated Biological Reactors (MABR) and associated plumbing and instrumentation. A simplified schematic of the BWP subsystem is shown in Figure 2. The four reactors are operated in series, with a recycle ratio 100x the influent flow rate. This reactor configuration can be modeled as a completely stirred tank reactor. The BWP recycle loop is instrumented with a bioluminescent dissolved oxygen sensor (Hach, XXXX) and a pH sensor (Hach, XXX), to provide real-time data on the operation of the system. In addition, a gas chromatograph (Agilent, xxxx), is integrated into the vent gas line of the BWP system, to quantify metabolically produced gases.

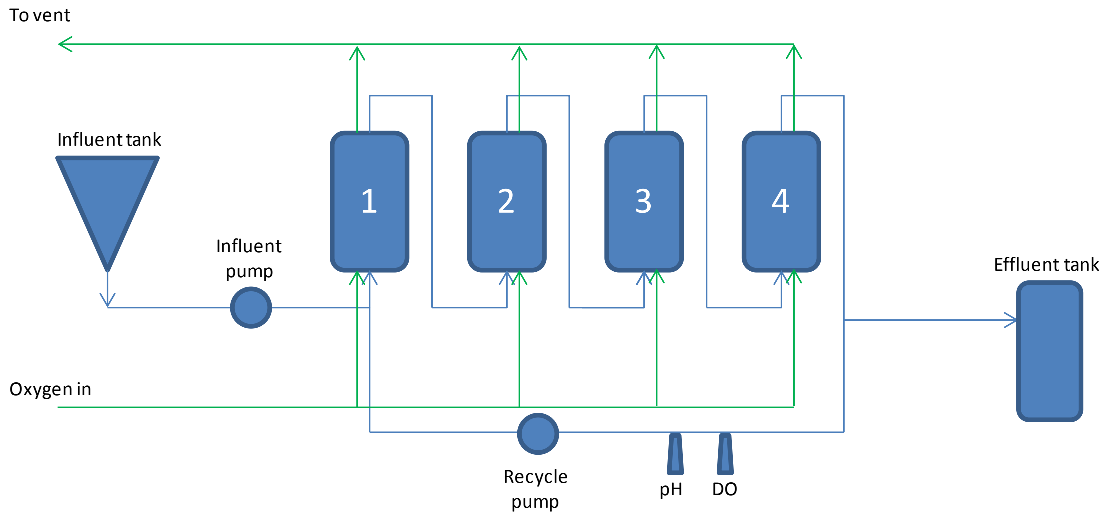

Figure 2. simplified biological water processor system. Valves, bypass, and drain lines are not shown.

Each MABR is an identical unit, based upon a design concept developed by researchers in the Civil Engineering Department at Texas Tech University (insert ref). It is an attached growth system, with bacterial biofilms attached to surfaces within the reactor. The MABR is designed to operate in microgravity and is operated as a single phase system. Oxygen, required for aerobic bacterial metabolism, is maintained within the lumens of silicone elastomer tubing (Dow Corning, XXXXX). Oxygen diffuses through the tubing, supplying oxygen to bacterial cultures growing on the outside of the tubing. The process by which the wastewater will be biodegraded is known as simultaneous nitrification/denitrification (SND). Oxygen is used by bacteria, which form a biofilm on the surface of the membrane, to convert the ammonium-nitrogen (NH^4-N), present as product of urea hydrolysis, into either nitrite (NO_2^-) and or nitrate (NO_3^-) in a process known as nitrification, as shown in Figure 3. Streamlined equations of urea hydrolysis and nitrification are shown in Equations 1 and 2.

Equation 1

Equation 2

The nitrite and/or nitrate is then used by other bacteria in the anoxic zone in the biofilm and/or the bulk fluid as terminal electron acceptors for carbon oxidation in a process known as denitrification, described in Equation 3. As the end of the process, the organic carbon and ammonia nitrogen present in the waste are mineralized to carbon dioxide and nitrogen gas:

Equation 3

The system will be operated to minimize the amount of oxygen used by the system in order to facilitate the preferential use of nitrite and nitrate over oxygen by the heterotrophic bacteria in order to drive the metabolic products toward CO_2 and N_2. Dissolved oxygen measurements of the fluid in the recycle line will be collected throughout the test to ensure that anoxic conditions are maintained in the reactor.

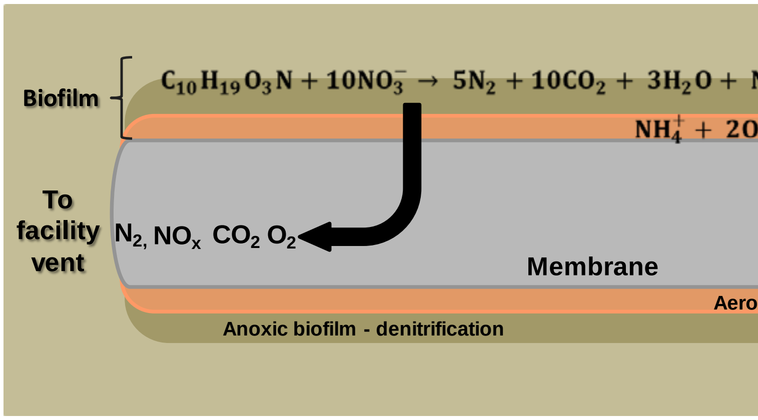

Figure 3. Metabolic reactions within the biofilm attached to the sur

Figure 4. Assembled MABR installed in integrated test stand.

2. MABR Design

The MABR was sized based upon an areal reaction rate of 1 g/m^2-d for both carbon and ammonium removal. Based upon the expected dissolved organic carbon and nitrogen loading for the wastewater, this resulted in a required membrane area of XX m^2. A margin of 33% was added to this area, to account for uncertainties in the laundry wastewater characteristics. This membrane area was divided among four reactors for ease of fabrication and assembly.

The MABR is designed to be operated at 20 psig, to maintain metabolic gases produced by the bacteria in solution. This is similar to the operation of previous biological water processors developed for use in microgravity (insert ref). However, it is known that the silicone elastomer tubes do allow for the diffusion of metabolically produced carbon dioxide and nitrogen from the water into the lumen of the oxygen tubes. One of the goals of testing is to determine the efficacy of the mass transfer of dissolved gases and the need for pressurized operation.

Current test plans assume operation with oxygen as the gas source. However, recent testing at Texas Tech has indicated that pure oxygen may result in excess oxygen mass transfer and inhibition of dentirification. The use of air would reduce the mass transfer of oxygen into the bulk liquid due to a decrease in oxygen partial pressure. The use of air in one or more of the reactors, in place of oxygen, will be assessed during the test.

The MABR was designed and assembled at Johnson Space Center, while its components were custom fabricated at various machine shops. The membranes are contained by header plates which were threaded by hand. Each reactor required approximately 12 hours to insert the tubes. The reactor is a shell within a shell design. The inner shell, known as the oxygen module, houses the main biological processes in the reactor. Each oxygen module holds 506 silicone elastomer tubes that run the length of the module. Each reactor contains 718 m of tubing. Oxygen caps at the top and bottom of each reactor connect the reactor to the inlet oxygen supply and mixed gas vent line at the outlet. The oxygen module provides structural support to counter the tension induced on the reactor by the elastomer tubes. The water shell provides liquid and pressure containment. An assembled MABR is shown in Figure 3.

B. Forward Osmosis Secondary Treatment System

The FOST functions as secondary treatment to the BWP to remove residual dissolved solids, residual ammonia, and suspended solids. It also provides a physical barrier to microbial and viral contamination. The FOST consists of a forward osmosis (FO) membrane module and a reverse osmosis (RO) system. FO and RO membranes are not effective at removing urea. A simplified schematic of the FOST is shown in Figure 5.

The FOST system has the FO upstream of the RO as a means to remove the remaining organic contaminants from the BWP. RO systems offer the potential to remove dissolved solids efficiently but perform poorly in the presence of high-suspended solids. Flux of water in the FO system is driven by osmotic pressure gradients, rather than high pressure as used in RO. Therefore, the FO tends to be less vulnerable to fouling by organic material. The FO uses a solution of high salt concentration, referred to as the Osmotic Agent (OA), to draw water from the BWP effluent through two spiral-wound cellulose triacetate membranes. BWP effluent is circulated on the feed side of the membrane, while a 5 to 10 g/L sodium chloride OA is circulated on the permeate side of the membrane. Water flows across the membrane toward the permeate due to an osmotic pressure difference. A reservoir on the FOST rack holds 15L of OA, and the level is maintained by a pressure level sensor and a control pump that pumps concentrated OA into the reservoir.

RO is a common water treatment process that effectively removes salts from wastewaters; however, RO membranes are highly susceptible to fouling due to the high pressures involved in driving the water through the membrane pores. The RO is used to remove salts from the FO product water and concentrate the OA for reuse by FO. As a result, water molecules in the wastewater diffuse through the membrane pores, and condense into nearly potable product water. The RO subsystem consists of two spiral-wound polyamide membranes organized into two stages. The first stage concentrates the OA for use by the FO subsystem. The product water from the first RO module is processed further in Stage 2. The product water from Stage 2 is the product water for the entire AWP system. The concentrate from these two stages are fed into the OA reservoir, which then recycled through the OA loop.

The FOST osmotic agent loop also incorporates an ultraviolet lamp to prevent microbial growth in the circulating OA.

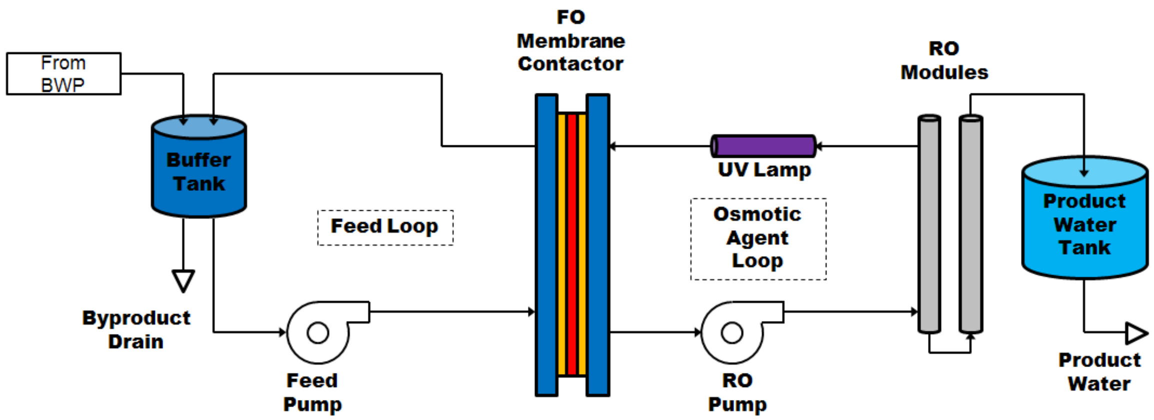

Figure 5. FOST flow diagram.

III. Test Overview

A. Objectives

The two primary metrics for the AWP integrated test are greater than 85% recovery of wastewater from an exploration wastewater model, and a 20% reduction in consumables from the current state-of-the art. In addition, the water quality produced by the FOST will be quantified. It is not expected that the BWP / FOST integrated system will produce potable water, however, it is necessary to characterize the water quality to determine the requirements for a post-processing system.

1. BWP

One of the primary objectives of the BWP system is to characterize the nitrification and organic carbon oxidation maximum loading rates to fully understand BWP system sizing. In order to do this, one or more of the MABRs may be bypassed to increase the effective loading on the system. Alternatively, the total wastewater loading on the system may be increased until the effluent water quality shows a negative impact. The optimum gas flow rate and composition through the silicone elastomer tubes will also be investigated. Finally, a carbon and nitrogen balance on the system will be completed on the BWP subsystem.

2. FOST

The initial objective of the FOST subsystem testing is to verify ability to process challenge solutions. This will be accomplished by operating the FOST while the BWP is operating in a degraded startup mode. Once the BWP subsystem is processing the wastewater load of four people, the effort will shift to quanitying the performance and comparing the test results to the initial results observed at Ames Research Center, using a different wastewater input. In the course of this evaluation, the water recovery rate will be quanitified, the flux loss due to membrane fouling will be characterized, and a cleaning frequency established. In addition, the power consumption of the system will be determined. If time permits, the life of the membrane modules will be determine.

B. Wastewater Definition

The exploration model for the AWP Integrated Test will be a mission with four crewmembers. In order to simplify wastewater collection over multiple test months, gender differences in the crew will be disregarded.

The wastewater stream will include urine, humidity condensate, hygiene, and laundry wastewater. Hygiene wastewater includes urinal flush, hand wash, shower, shave and oral hygiene water. The wastewater model is summarized in Table 1. The wastewater collection and transport system, part of the AWRSDF, will be used to collect hygiene wastewater.

Table 1. Wastewater composition.

Wastewater (WW) Type		WW Per Event (kg/event) in liters	Events Per Day Per Crewmember (event/day-CM)	Total WW for Four Crew (kg/day-crew) in liters	Personal Care Products
Urine		1.2 (per day)	N/A	4.8	
Hygiene	Oral Hygiene	0.1	2	0.8	1.0g of Arm & Hammer Toothpaste
Hygiene	Hand Wash	0.125	8	4.0	No-Rinse Shampoo, NASA Formulation. 1.5g for hand wash, 25.0g for shower
Hygiene	Shower	6.0	1	24.0	No-Rinse Shampoo, NASA Formulation. 1.5g for hand wash, 25.0g for shower
Hygiene	Shave	0.15	1	0.15 (one CM of four will shave)	0.8g Neutrogena Men Shave Cream
Hygiene	Urinal Flush	0.3 (per day)	N/A	1.2	
Humidity Condensate		1.95 (per day)	N/A	7.8	
Laundry		≤45	N/A	≤45	15g of Seventh Generation Natural 2X Concentrated Laundry Liquid (Free and Clear)
			TOTAL	87.75	

1. Urine

The AWP Integrated Test will utilize a total daily volume of 4.8kg of urine. Total urine production per crewmember is approximated at 1.2kg (or 1.2L) a day. This quantity is based upon historically observed output for ISS crewmembers and was previously used in other advanced life support concept testing, such as the Distillation Comparison Test .[8] More than four donors will be used to collect a total of 4.8kg of urine.

2. Humidity condensate

Total humidity/condensate generated per crewmember is approximated at 1.95kg (1.95L) of latent (1.85kg) and exercise-induced water vapor a day (0.1kg). Therefore, the total daily contribution will be 7.8 kg/day for a mission with four crewmembers. This volume was also used for the Distillation Comparison Test and rationale is documented in Table 21 of JSC 47176 .[8]

Simulated humidity/condensate will be utilized for this test, prepared in accordance with Verostko et al. .[9] Humidity/condensate is the only simulated waste stream included in this test, necessary due to the test subject support, time and expense necessary to generate 7.8L of human-driven humidity/condensate per day.

3. Hygiene Wastewater

Total shower wastewater per crewmember is approximated at 6.0kg (or 6.0L) of wastewater per day. Therefore, the total daily contribution will be 24.0 kg/day for a mission with four crewmembers. The test subject will utilize 6.0kg DI water and 25g of No-Rinse Shampoo at each shower event. NASA No-Rinse Shampoo is NASA part number SEZ33114865-302. This special formulation for NASA is currently in use on-board ISS and is likely the same or similar to products that will be used on future, long-duration exploration missions.

Total hand wash wastewater per crewmember is approximated at 1.0kg (or 1.0L) of wastewater per day. This represents 0.125kg of wastewater generated during eight hand washings a day. Therefore, the total daily contribution will be 4.0 kg/day for a mission with four crewmembers. The test subject will utilize 0.125kg DI water and 1.5g of No-Rinse Shampoo at each hand wash event.

Total oral hygiene wastewater per crewmember is approximated at 0.2kg (or 0.2L) of wastewater per day. This represents 0.1kg of wastewater generated during two daily oral hygiene events per crewmember. Therefore, the total daily contribution will be 0.8 kg/day for a mission with four crewmembers. The test subject will utilize 0.1kg DI water and 1.0g of Arm and Hammer Dental Care, Advanced Cleaning (UPC: 3320018370) at each oral hygiene event. This toothpaste was selected based upon testing performed as part of the Distillation Comparison Test.[7]

Total shave wastewater per crewmember is approximated at 0.15kg (or 0.15L) of wastewater per day. This test assumes that one male crew member (of three) would prefer to wet shave, generating a total of 0.15L of shave wastewater per day for all four crew. The test subject will utilize 0.8g of Neutrogena Men's Skin Clearing Shave Cream, (UPC: XXXXXXX) for each shave event. Similar to the rationale for selecting the toothpaste, the Neutrogena Men's Shave Cream was initially chosen for the Distillation Comparison Test, having generated the least amount of solids when compared to other shave gels.[8]

4. Laundry

Currently, there is no laundry capability on-board ISS. Clothing is worn and rotated, then discarded. However, in a long-duration, exploration mission, some trade studies indicate that use of an in-flight washing machine and recovery of the wastewater is cost-effective, since continual supply of unworn crew clothing is not feasible. Therefore, the AWP Integrated Test will utilize laundry in the combined wastewater stream and the governing assumptions for modeling a long-duration, exploration mission with laundry capabilities.

The AWP test will utilize an Asko W6903 washing machine located in the AWRSDF. The washing machine is supplied with facility DI water. This washer will produce to produce approximately 30kg of wastewater from 2.9kg of soiled clothing. Laundry will be washed on alternate days.

5. Laundry detergent selection

No NASA standard laundry detergent currently exists. The primary requirements for laundry detergent selection was elimination of fragrance, color, and other unnecessary compounds for spaceflight, such as optical brightners. Accordingly, three commercial laundry formulations were identified as candidates for the AWP test. These candidates include Seventh Generation Natural 2X Concentrated Laundry Liquid, Free and Clear, on the basis of the elimination of unnecessary additives, Tide Pods, on the basis of concentration, and AATCC (need to define acronym) standard detergent, as the industry standard for detergent tests. Personnel at Kennedy Space Center conducted a series of experiments using an Oxygen Biosensor System (OBS) (BD Biosciences, San Jose, CA) to determine the impact of these three candidate detergents on the carbon oxidation reactor effluent microbial community. Each of the detergents was diluted to an operating concentration according to the manufacturer's recommendations, assuming a standard high-efficiency average water volume of 60 L per wash load. The OBS plates were loaded with equal volumes (100 µL) (v:v:v) of dilutions of carbon oxidation reactor effluent, a 3x carbon source and/or dilutions of detergents, and the volume was boosted to a final of 300 µL with sterile molecular-grade water when required. For each assay, controls were included to produce negative and positive responses utilizing the components required for each plate. After each plate was loaded, it was sealed with a Titer-Top (Diversified Biotech) plate cover to prevent additional external oxygen from entering the wells and altering the consumption response. Each of the fluorescent assays were evaluated on the BioTek Synergy HT plate reader for 72 hours with kinetic readings acquired every 15 minutes. Overall, the 7th Generation detergent had the least impact on the microbial community and the AATCC standard caused the most significant decrease in the respiration rate of the microbes with the Tide Pods falling in-between the other two detergents.[4] Therefore, the 7th Generation detergent was selected for use during the AWP test.

C. Test Operation

Following completion of test system buildup and functional checkouts, the BWP subsystem will be inoculated with a bacterial consortium. This bacterial suspension originates from an terrestrial nitrification wastewater plant, and have been further cultured by enrichment with urine as a growth substrate. This culture was developed at Texas Tech and provided to the personnel at JSC. Depending upon the final cell concentration, this culture may be augmented with additional wastewater treatment plant cultures prior to inoculation.

The inoculation phase of the test is expected to last four – six weeks. During this period, bacteria will gradually attach to the surface of the silicone elastomer tubes. The system will initially be operated in a recycle mode using a 10% urine wastewater solution. As nitification is established, the urine load will be gradually increased and the system will transition to flow-through operation. Humidity condensate, hygiene and laundry wastewater, will gradually be introduced based upon system performance. During this inoculation phase, the FOST system will be used to process any effluent produced by the BWP system. This will enable an assessment of the FOST operation when the BWP is operating in a degraded mode.

Once inoculation is complete, the test will transition to standard operations. Because laundry is planned to be run on a two-day cycle, the wastewater volume will fluctuate on a daily basis, between 43 and 73 liters / day. Wastewater inputs will be collected during each test day.

Regardless of the daily loading, the BWP will operate at a constant influent flow rate. The BWP system will transition to a periodic operation mode. The BWP will transition to processing mode at approximately 4 pm each day, and produce effluent at a constant rate until the wastewater influent tank reaches a low level. The total duration of this "flow-through" mode will vary depending upon the mass of wastewater in the influent tank. Once the influent tank reaches a minimum, the BWP will return to recycle mode and the effluent tank will be full.

When the BWP cycles to recycle mode, operation of the FOST will begin. Depending on the daily wastewater load, the FOST will operate for 4 – 5.5 hours. The FOST will operate only during the day, while test personnel are present. This cyclic operating mode enables a shared tank between the BWP and FOST, and provides the ability to quantify the recovery rate of the FOST. When the FOST completes processing of the BWP effluent tank, the residual wastewater in the tank will be weighed, sampled, and discarded as brine.

IV. Conclusion

The AWP integrated test is expected to be inoculated in early April, 2013. The test will run until September 30, 2013. The results of this test will provide additional sizing and performance information for disruptive biological and membrane based technologies to support long duration human space exploration.

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