Habitat Water Wall for Water, Solids, and Atmosphere Recycle and Reuse

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ABSTRACT

Current space system architecture is severely limited by launch cost associated with the mass of building and radiation protection materials, limits to the size (volume) of habitat elements that can be lifted, and the life cycle design requirements for technologies that provide recycle of life support materials, particularly air and water. This study proposes a system for membrane based water, solids and air treatment functions, which are embedded into the walls of inflatable habitat structures. They provide potentially radical mass reuse and structural advantages over current mechanical life support hardware operating within rigid habitat envelopes. This approach would allow part of the water and air treatment, and all of the solids residuals treatment and recycle, to be removed from the usable habitat volume while providing a mechanism to recover and reuse water treatment residuals (solids) to strengthen the habitat shell, provide thermal control, and radiation shielding. The same embedded membrane treatment elements would first, for a time, provide primary (1st stage) wastewater treatment, then provide solids accumulation and stabilization, and lastly would become a permanent structural element for the mature habitat shell. Secondary air treatment membrane elements similarly located are also considered as potential future additions to the treatment architecture.

EXECUTIVE SUMMARY

Over the last 20 years NASA human planetary/lunar exploration programs have come and gone. However, one fact remains constant across all of them. They are too expensive. Several different Administrations and Congresses have again and again turned down NASA human planetary exploration programs due to costs.
What is needed is a radical departure from the status quo which would allow the cost of human spaceflight to be reduced by an order of magnitude. To do this will require a new approach to supporting humans in space. For example the cost of providing life support for the crew will have to be drastically reduced. A recent study for a proposed lunar outpost (4 person 180 day) estimated that life support costs would be on the order of 15,400 lbs (7000 kg) of launch mass. This estimate is based on using next generation life support technologies derived from existing International Space Station (ISS) systems [1]. This does not include spares and redundancies, which could easily double this figure.
Current space system architecture is also severely limited by launch costs associated with the mass of building and radiation protection materials, and limits to the size (volume) of habitat elements. The membrane water wall concept proposes a system for membrane based structural, thermal, radiation, water, solids and air treatment functions that are embedded into the walls of inflatable or ridged habitat structures to provide novel and potentially game changing mass reuse and structural advantages over current mechanical life support hardware .
This study provides the first evaluation of this concept. It focuses primarily on water and solids treatment. Sizing calculation and functional concepts are developed for this application. Experimental work is provided that focuses on evaluating the performance of passive membrane based forward osmosis treatment of wastewater and dewatering of solid and brine wastes. Air treatment is address from a theoretical perspective and thermal, radiation and structural analysis is left for definition in future studies. Specifically, the principals and practice of forward osmosis membrane treatment is discussed sighting examples of functional systems to provide a background and examples of the feasibility of forward osmosis treatment of wastewater. The data generated from these example technologies is then used to develop sizing calculations for wastewater treatment water wall membranes including process step examples of how the proposed system would work. Experimental results are then provided to demonstrate that performance data and assumptions used for sizing are applicable to full treatment to a dried solid residue.
A detailed discussion is then provided on solids and residual processing in the membrane walls for both planetary and transit mission wastewater profiles. This discussion also addresses the formation of building materials from these treated residuals. A theoretical discussion is then provided for air trace contaminate control concepts and some alternative air and thermal control approaches. Finally a practical near term operational

approach to developing the water wall concept in small steps by integrating the ideas into ISS cargo transfer bags (CTD's) and reusing them to accomplish life support, radiation protection, and structural functions is described.

BACKGROUND

Principles and Practice of Forward Osmosis Membrane Water Treatment

The membrane wall (water wall) concept begins with the use of flexible low pressure membrane elements for wastewater treatment. These osmotically driven membrane elements use non-hydrostatic pressure driving forces to drive both liquid and vapor flux across a membrane. Hydrostatic driving forces are utilized in most familiar membrane based liquid/water treatment processes (Figure 1). These processes include both reverse osmosis (RO), which is a small pore size membrane diffusion based separation process, and microfiltration (MF) which generally utilizes a larger pore size membrane and is less selective, but is also more resistant to fouling than RO. RO and MF both require a high pressure differential to drive water flux across the membrane and are thus characterized by robust pressure vessel construction, heavy pumping hardware and relatively high energy consumption requirements. These requirements have not only dictated how these specific types of membrane systems are constructed, but have also generated a specific mental image for how membrane systems must be constructed which does not apply to other membrane applications, and is not optimal for integration into space structures.

Membrane Process Paradigms
Current membrane paradigms are dominated by conventional Reverse Osmosis (RO) and Microfiltration (MF)

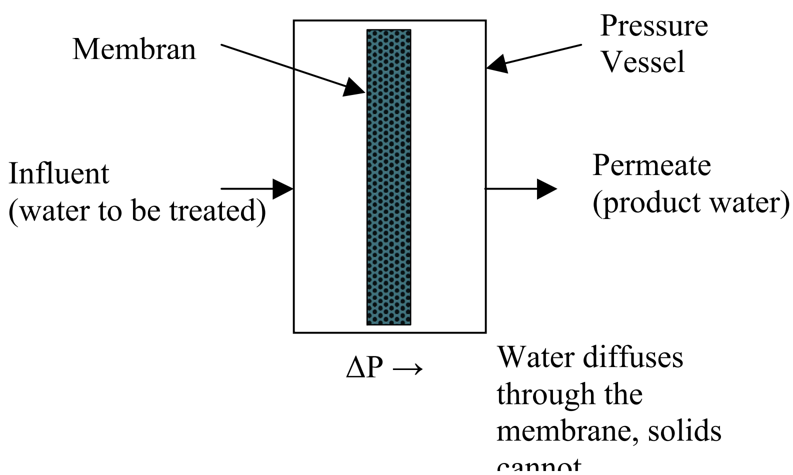


Figure 1 Current membrane paradigm requiring pressure containment.

Membrane systems that employ different driving forces such as forward osmosis (FO) or vapor transport (i.e. membrane distillation and/or osmotic distillation) [2], or operate on entirely different principles such as membrane bioreactors, can and should be constructed in completely different ways. FO for primary water treatment employs the osmotic pressure difference between wastewater influent and a salt water receiving brine to drive flux in a primary treatment step that requires no hydrostatic pressure [3] (Figure 2). This process is generally followed by reconcentration of the receiving brine by conventional RO.

Forward Osmosis (FO)

Used to reduce fouling in the initial stage of membrane treatment for highly contaminated waste streams with no pressure vessel required

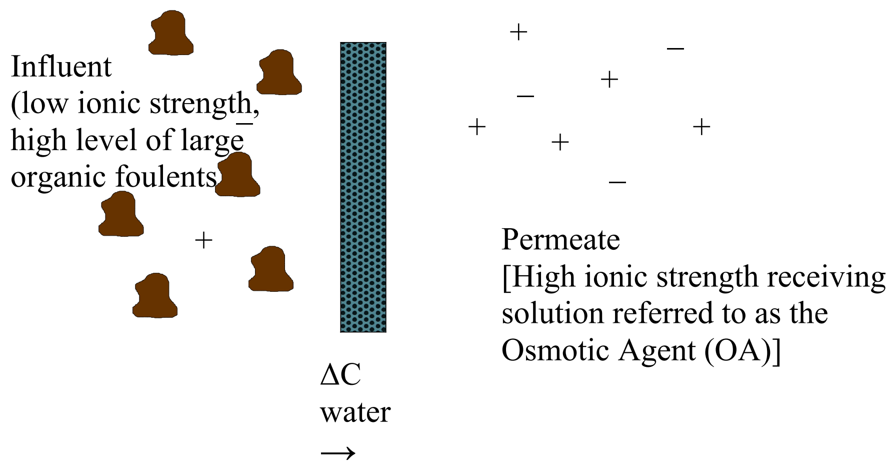


Figure 2 FO process explanation; Note that ΔC is the concentration gradient rather than ΔP the hydrostatic pressure difference used in RO or MF.

Equation 1 shows the relationship between water flux across the membrane and both the hydrostatic and osmotic pressure differentials across the same membrane [3]. This equation is stated in the form most relevant to RO or MF as flows:

$$F_w = A_c (\Delta P - \Delta\pi) \qquad \text{Eq. 1}$$

Where:

F_w = Total water flow across the membrane in $l/(m^2\ hr)$

A_c = The membrane flux resistant constant in $l/(m^2\ hr\ atm)$

ΔP = Hydrostatic pressure (atm)

$\Delta\pi$ = Opposing osmotic pressure potential (atm)

In FO, the hydrostatic pressure supplied is zero and the same governing equation can be rearranged and simplified (Eq. 2) to read:

$$F_w = A_c\ \Delta\pi \qquad \text{Eq. 2}$$

As a result of Equation 2, it can be seen that the membrane can be configured such that no hydrostatic pressure exists across the membrane and thus no pressure housing and/or support is required. This allows the membranes to operate in soft bags packed within the flexible wall materials of an inflatable habitat, thus creating the water inflated water wall.

In most cases some hydrostatic pressure is still present as a result of the act of supplying the membrane with a flow of liquid. This flow is required for both sides of the membrane and should be nearly balanced (i.e. ΔP is zero across the membrane). In this situation, the hydrostatic pressure either could be in the forward or opposing direction relative to the intended water flux direction, but in either case will be negligible in comparison to the osmotic pressures.

Using the common example of urine (5g/L as NaCl) on one side of the membrane and deionized water on the other, the resultant osmotic pressure is on the order of 58 psi at the membrane. Urine is expected to consist of approximately 5 g/l of NACl based on previous research[2]. In a flexible membrane bag inside a flexible external plastic bag envelope construction arrangement, this 58 psi is acting on the membrane [5] and results in a pressure equalizing flux of water across the membrane. This is due to equalization of forces on a microscopic level. Therefore, no pressure vessel is required to support the process. The hydrostatic forces required to move water in and out of the membrane element on either side of the membrane are less then 10 psi in a well designed system.

When FO is used as a primary treatment step, virtually any wastewater can be treated by membrane processes regardless of its fouling potential [5, 6]. This potentially includes the dewatering of sludge by membranes. Following FO, by conventional RO allows RO quality water treatment for water that would otherwise completely foul and destroy an RO system. In a combined FO/RO system, the bulk of primary treatment is done by the FO element with a re-concentrating RO polishing step completing the primary treatment of wastewater within a highly reduced system volume. Post or polishing treatment would be required but oriented to trace contaminants in the less than 50 mg/L range total in terms of residual total organic carbon (TOC).

Thus, FO primary treatment can be accomplished using a flexible bag based water process element rather than a pressure vessel. Figures 3 and 4 show a 1.5 L to 2.0 L cellulose triacetate membrane treatment element. This FO bag element can effectively give an RO like membrane treatment while drawing the water component of seawater or urine into a high sugar drink mix (with the sugar providing the osmotic pull). This is the basis for the Light Weight Contingency – Water Recovery System (LWC-WRS). Approximately 97% of seawater's total dissolved solids (TDS) or salts are rejected, and the sugar in the drink mix provides the necessary driving force for water recovery due to the osmotic pressure differential. FO bag treatment for the LWC-WRS has been well studied and may provide a model for a more optimal mode for first stage membrane treatment than a conventional membrane treatment element design can provide. The FO element in the wall embedded membrane configuration would be fabricated on a larger scale than the LWC-WRS FO bag, but would have essentially the same construction and treatment properties (Figure 5).

Figure 3 FO flux test run in progress for evaluating four different liquid food products as the osmotic agent and seawater as source water in the LWC-WRS application.

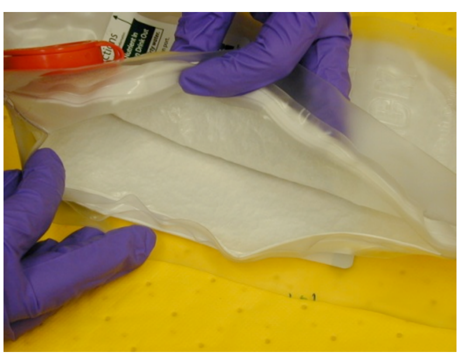


Figure 4 X-Pack ® FO membrane bag opened to show internal cellulose triacetate membrane.

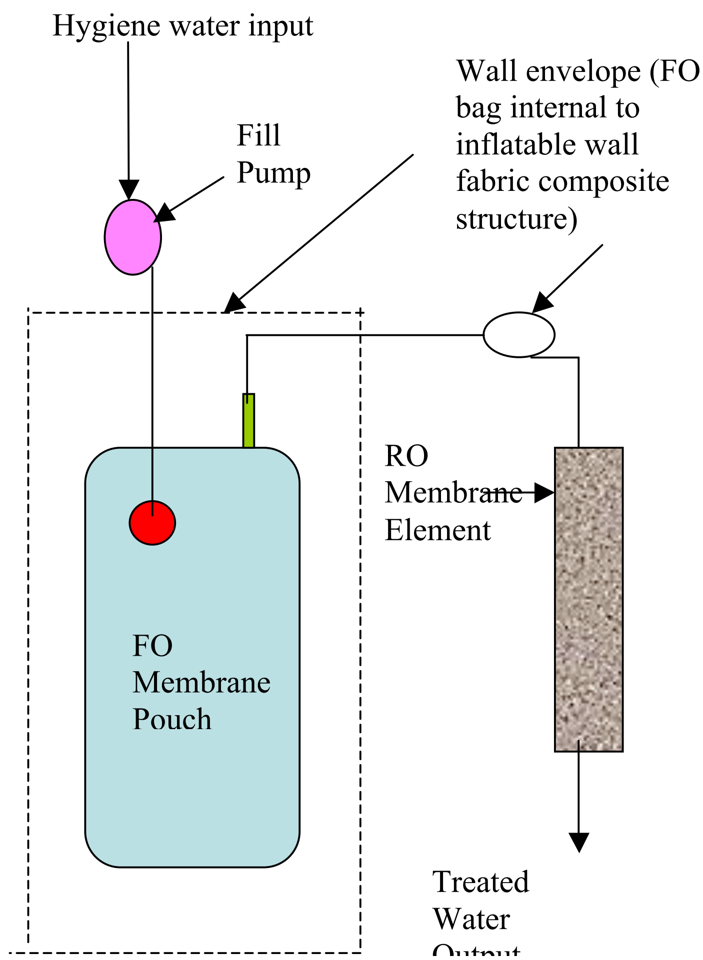


Figure 5 New FO/RO Water Wall System Concept

The LWC-WRS is a simple disposable system that demonstrates how the embedded FO membrane would work. Alternatively, the Direct Osmotic Concentration (DOC) system is a sustainable and long-term (rather than disposable) wastewater process that demonstrates how the FO membrane element would be integrated into a system capable of providing potable water recycle for an indefinite period of time. The DOC system is an effective gray water recycle treatment process, but could achieve even more effective mass and volume advantages if the FO treatment process was reformatted into embedded wall structures.

Figure 6 Flat sheet FO membrane element.

Figure 7 Spiral wound FO membrane elements as mounted in the DOC system.

FO/RO combined systems (like DOC) are currently undergoing research and development by NASA. Various primary FO element construction formats have been researched and include both flat sheet (Figure 6) and spiral wound (Figure 7) configurations for DOC, and this process has been applied to purposes as diverse as food processing [5] and treatment of land fill leachate [6]. Both DOC membrane hardware configurations are extremely similar, in shape and appearance, to pressurized hydraulic applications for membranes; however, they may be less than optimal for the FO process. It should also, therefore, be noted that the commercial spiral wound FO membrane element, when employed in the Water Well ® commercial application shown in Figure 8, is used with no external containment (housing) around it, but rather is simply submerged (in the contaminated water to be recovered) in the tub shown. A sugar water drip is supplied to the axial tube seen at the center of the membranes in Figure 9, via the IV like bag (intravenous drip bag) and plastic tubing visible in Figure 8.

Figure 8 The Water Well ® commercial application for the spiral wound FO elements similar to those used in the DOC project.

Figure 9 Spiral wound FO membranes

Due to the potential membrane surface area advantages generated by including FO bag-like elements into wall construction, scaling up the bag and using it in FO/RO combined systems may provide the optimal possible membrane treatment for hygiene water (the space systems equivalent of gray water, primarily from showers and laundry).

Results from the DOC study indicate that primary treatment of hygiene water is acceptable for drinking water treatment. FO bag element treatment potential can also be extrapolated from LWC-WRS testing results, which would indicate that the flexible bag element format is equally effective when compared with more traditional and less flexible membrane element configuration (as used in DOC) for FO stage treatment.
From these results, it is apparent that a next generation FO/RO system could be developed in which all habitat gray water (as well as pretreated urine and humidity condensate) could undergo an initial FO treatment in flexible wall embedded bag elements, be stored in these wall embedded elements as relatively clean salt water, and then be harvested as needed through the use of simple and small foot print RO system like those used on small sailing crafts to desalinate seawater during open/trans ocean racing. In this type of a system the majority of the wastewater and wastewater treatment system volume (and mass) would be dedicated to relatively clean salt water bladders embedded in the wall and providing water/radiation shielding without competing for habitat volume.

This approach would be particularly valuable in inflatable habitat construction (Figures 10, 11, and 12) where the embedded wall elements would be extremely compact, lightweight and flexible prior to the introduction of wastewater. It should also be noted that the FO membrane provides a membrane disinfection level separation for the water that passes through it. Thus, water treated and then stored in the wall as salt water would be initially sterile.
Both the LWC-WRS and DOC projects have been reported on extensively in previous International Conference on Environmental Systems (ICES) proceedings papers. For LWC-WRS DOC data see ICES proceedings papers 2006-01-2083, 2007-01-3037 and 2007-01-3035 [7][8][9]. An additional technical cross reference list on these projects is included following the regular reference section at the end of this document, as is current contact information for the authors.

Figure 10 Inflatable habitat concepts (Image by John Frassanito & Associates, courtesy of NASA.

http://library.thinkquest.org/05aug/01145/pics/hotel/css/transhab.jpg

Water Wall bags elements in the inner liner layer

Figure 11 Inflatable habitat structure showing inner liner layers and the location of FO bag elements. Images by John Frassanito & Associates, Courtesy of NASA.

Figure 12 Embedded Water Wall bag element layers as embodied in the X-Pack®.

APPROACH

This study provides the first conceptual evaluation of the concept of using a habitat water wall for water, solids, and air recycle and reuse. It focuses primarily on water and solids treatment. Sizing calculation and process concepts are developed for this application to evaluate rough order of magnitude feasibility of the approach.

Experimental work is provided that focuses on evaluating the performance of passive membrane based forward osmosis treatment of wastewater and dewatering of solid and brine wastes. Air treatment is address from a theoretical perspective and thermal, radiation and structural analysis is left for definition in future studies.
Specifically, the principals and practice of forward osmosis membrane treatment is discussed sighting examples of functional systems to provide a background and examples of the feasibility of forward osmosis treatment of wastewater. The data generated from these example technologies is then used to develop sizing calculations for wastewater treatment water wall membranes including process step examples for how the proposed system would work. Experimental results are then provided to demonstrate that performance data and assumptions used for sizing are applicable to full treatment to a dried solid residue. A detailed discussion is then provided on solids and residual processing in the membrane walls for both planetary and transit mission wastewater profiles. This discussion also addresses the formation of building materials from these treated residuals. A theoretical discussion is then provided for air trace contaminate control concepts and some alternative speculative air and thermal control approaches. Finally a practical near term operational approach to developing the water wall concepts in small steps by integrating the ideas into ISS cargo transfer bags (CTD's) and reusing them to accomplish life support, radiation protection, and structural functions.

RESULTS

Sizing Calculations for Water Wall Membranes

Using a combination of DOC and LWC-WRS project results, an embedded FO membrane cell containing a FO pouch that is roughly similar to the LWC-WRS FO membrane bag in construction, could reliably process 4 L/hr per square meter of wall area, or 96 L/m^2 -day. This indicates that based on an early planetary base wastewater production rate, which is projected at 11.85 kg/crewmember day [10], 8 crewmembers would be served by 1 m^2 of active membrane wall area. Assumed transit volumes would not include substantial amounts of hygiene water input and, as set by the same referenced operations research, would be closer to 3.53 kg/crew day. Thus 1 m^2 of membrane wall area treating transit mission water (or any long-term free space habitat wastewater) could service a maximum of 27 crewmembers.

It is unlikely that 27 crewmembers will be housed in a space habitat in the foreseeable future, so this overcapacity will be used to extend system life. Also, it should be noted that since both wastewater and reject brine have a specific gravity close to 1.0, 1 kg and 1 liter of the material are consider interchangeable units of measure throughout this discussion.

At this rate of use, an active membrane would last 10 to 20 cycles depending on the solids loading rates, based on commercial product use data and recommendations. Bag sizing and distribution would be organized so that the service life of any given bag would not exceed one month, and would correspond to approximately 10 cycles for transit/free space mission wastewaters and 20 cycles for planetary base habitats.

Cycles are dictated not by membrane life but reject accumulation rate. This in turn is dictated by water recovery rates of 90% for urine dominated transit wastewater and 95% for hygiene waste dominated wastewater (soapy gray water). These recovery rates are projected based on LWC-WRS urine treatment testing results for transit scenarios and DOC projected FO element hygiene water recovery rates for planetary base assumptions. The reject brine in both cases would be forced back into the previously exhausted membrane bags and the rate at which these expended bags filled to capacity with reject brine would dictate the rate of progression (rather than membrane life which would never be approached). Figures 13, 14, 15, and 16 illustrate the process described above.

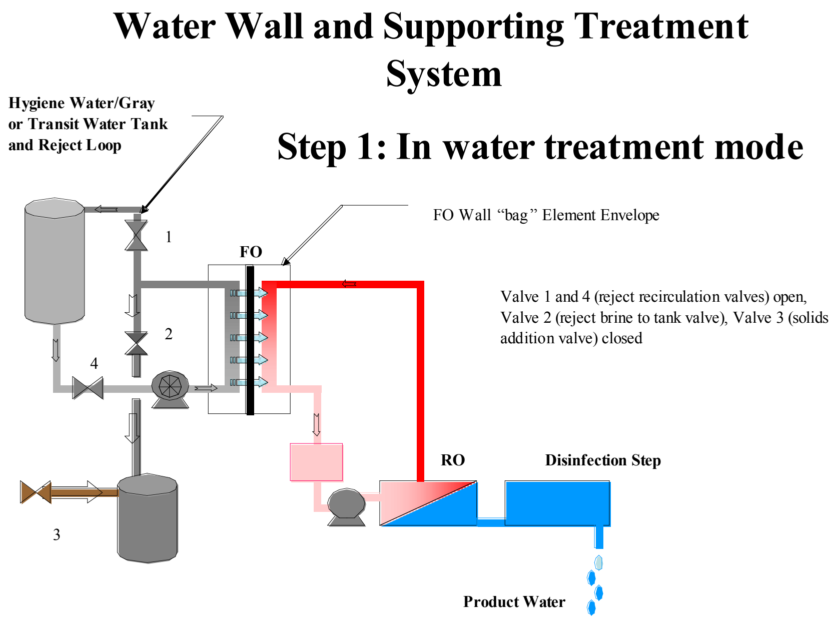


Figure 13 Water treatment mode operation, i.e. the day to day water treatment system mode for the bag (labeled FO)

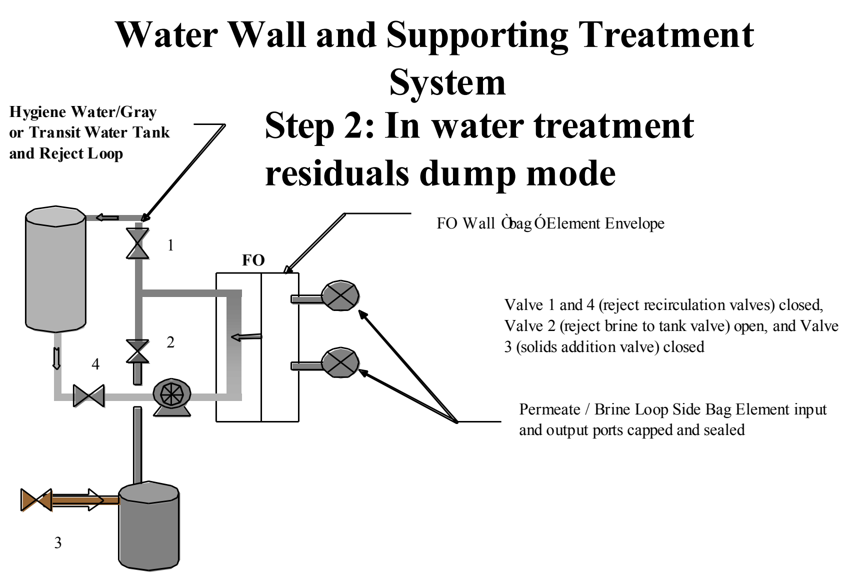


Figure 14 Residuals dumping, when the individual bag has treated all it can, the rejected solids are rejected to a high solids wastewater tank. Steps one and two are cycled 10 to 20 times for each bag.

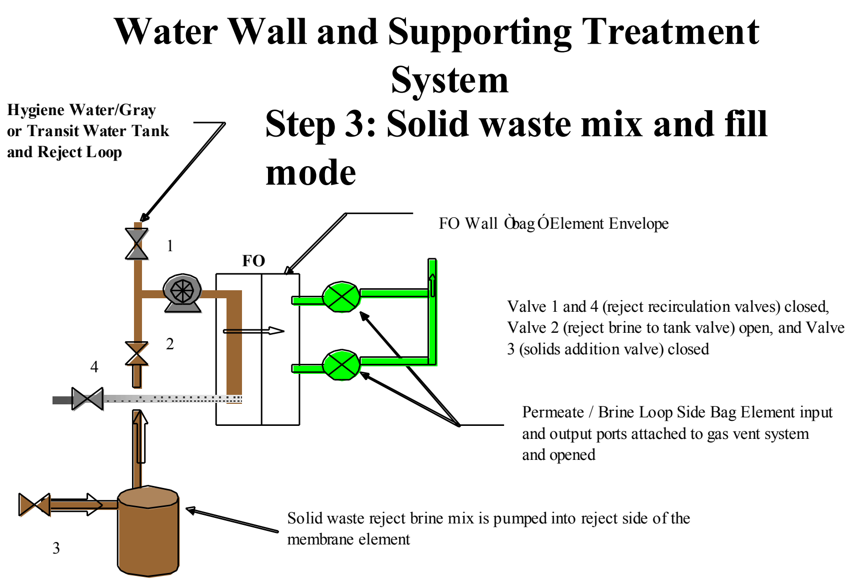


Figure 15 Solid waste injection. Once the individual bag's treatment capacity is used up (10 to 20 treatment runs) the high strength reject is mixed with other solid wastes to undergo digestion and sludge drying in the bag.

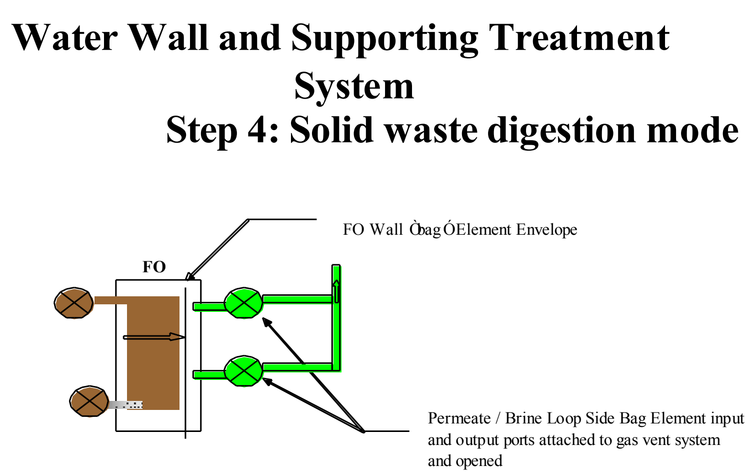


Figure 16 Solid waste digestion mode operation

This process would leave a stabilized, concentrated salt water brine residual in the wall 5 cm (2 inches) thick after treatment. Filled with stabilized brine at the end of the active water treatment phase, the bag would contain approximately 0.51 m^3 or 510 liters of water/reject brine weighing 510 kg total (water and bag construction). Bags could be layered to provide thicker water walls (10, 15 or 20 cm) as required, but all other conditions would remain the same (Table 1). The reject accumulation rate would be 0.35 kg/crew day for transit and 0.59 kg/crew day for planetary habitats. This results in an area use rate of 1400 crew days per m^2 for transit and 860 crew days per m^2 for planetary habitats. It should be noted that bags could then be layered to any desired thickness.

The extremely low rate of accumulation of reject volume is a result of the water being extremely effectively treated and conserved, and the fact that up mass investment for the supply of fresh water is fully utilized. Water recovery rates of 90% to 95% are achieved and are competitive with other ELS water processing options. However, over long periods of continuous occupation the 100% utilization rate dictates that a substantial shielding layer of low cost volatile resources based on the 5% to 10% reject will be accumulated, and no further cost for down mass or waste handling will be incurred.

Table 1 Per Layer Membrane Wall Specifications.

	Transit	Planetary
Wastewater Volume Requiring Treatment (kg/Crew day)	3.53	11.85
Active membrane area required (m^2 /Crewmember)	0.036	0.12
Active area treatment capacity required at a 4 L/hr production rate (Crewmember days/m^2)	1400	860
Cycles per bag	10	20
Water recovery rate	90%	95%

The most substantial benefit of taking this approach from a near term mass and volume perspective is the FO membrane element mass and volume advantages, particularly when used in inflatable habitats. Prior to treatment, in a packed inflatable habitat bundle, 1 m^2 of membrane bag area would weigh approximately 1.7 kg and have a packed volume of 0.082 m^3 per square meter of membrane area (0.082 m^3/m^2). Packing volumes are based on the LWC-WRS FO bag hardware and indicate a first stage FO treatment return of 850 crew days per kg or 2,990 kg of wastewater treated per kg of membrane bag launched. This does not include the second stage RO and any final processing step, but it does indicate that the cost of primary treatment (done by FO) becomes an insignificantly small mass penalty in comparison to more mechanical ELS system elements.

These values are arrived at using the commercially available FO bag as follows:

Area = 15 cm X 27 cm X 2 sided membrane bag = 0.081 m^2 per bag

Bag weight is ≈ 140g

1 m^2 = 1/0.081 bags which weighs 12.3 X 140g

This gives 1.7 kg/ m^2

Dry packed volume per bag is:

12.3 (30 cm X 17 cm X 1.3 cm) X 10^{-6} = 0.0082 m^3

RO and other post processing is not included but will be small because the bulk of the contaminant removal will be accomplished in the FO process. This means the mass and volume for the RO and polishing steps will be highly optimized.

Dewatering to Wet Solids Level Concentration using Transit Ersatz

An experimental program was completed as part of this work that evaluated the ability of the forward osmosis process to dewater a simulated ersatz solution representing spacecraft wastewater. The objective was to verify past experimental work completed using actual wastewater and to evaluate using the technology to fully dry wastewater residuals and solid wastes for further processing in the water wall architecture. To complete this work a commercially available forward osmosis technology called the X-Pack, available through Hydration Technologies Inc., was used.

The Water Wall X-Packs were tested on a three to four day weekly schedule in which they are filled with simulated ersatz solution and simulated salt water is placed on the other side. The wastewater/solid waste ersatz was placed in the green port and the salt water was placed in the red port. For the first Test Bag 1, 70g/l of NaCl was poured in the red port side of the x-pack and 1000ml of ersatz mixture was poured on the green port side of the cellulose triacetate membrane treatment element to test for forward osmosis primary treatment.

Data points are then collected every two hours in a six-hour run time with a final data point at 24 hrs. Information measured during the data points is the reject concentrations on the green port side of the membrane in order to calculate the flux rate. Osmotic Agent measurements of the red port side of the membrane x-pack are measured at the beginning of each day's run and the end of the run. A 250ml volumetric flask was used for measurement. At the end of each day's run the x-pack was re-charged by pouring 500ml of fresh NaCl in the red port side and leave it over night. The green port side is not re-charged until the following day just before starting the run.

Solid waste tests using simulated human feces ersatz mixture and the byproduct brine of the wastewater tests was also completed. The solid waste/byproduct ersatz was poured in the

Figure 17 Hydration Technologies X-Pack Forward Osmosis Treatment Bag

green port side. These tests used an 300g/L NaCl solution on the red port side and collected data once a day at 3pm and then re-charged the draw solution with a fresh 300g/L NaCl solution.
For the wastewater tests each bag was reused 10 times for a total of 30 runs completed using 3 different bags. For the solid waste tests the 3 bags used in the wastewater test were used. Each bag was used to conduct one multi day solid waste dewatering test.

Experimental Procedure
Preparing Liquid Ersatz:

1) Label three 1 liter flasks C1, C2, C3 and add 500 ml of DI water to each. For each concentrate, add the ingredients listed in the Ersatz Wastewater Formulations for Testing Water Recovery Systems paper for each respected concentrate.
2) Mix thoroughly between ingredients until each has gone into solution. Dilute each flask to 1 liter with DI water and mix thoroughly to mix concentrates. Cap all concentrates and store under ambient conditions
3) 1 liter working solution: Add 300 ml DI water, 100 ml of concentrate 1, and 100 ml of concentrate 2 to a 1-liter flask and mix thoroughly then add 100 ml of concentrate 3 and dilute with DI water to 1 liter and mix thoroughly

Recipe Used for Ersatz Mixture:
Dish starting Wt: 4.3204g

Concentrate 1 (10x)- **Organics**	Target Wt
Urea	52.021g
Creatinine	5.221g
Histidine	0.958g
Taurine	0.556g
Glutamic Acid	1.660g
Glucose	2.636g
Ammonium Citrate	12.340g
Ammonium Formate	1.466g
Ammonium Oxalate **Monohydrate**	0.665g

Concentrate 2 (10x)- **Inorganics**	Target Wt
Sodium Chloride	23.126g
Magnesium Chloride **Hexahydrate**	5.483g
Potassium bicarbonate	2.197g
Potassium hydrogen **carbonate**	0.474g
Potassium monobasic **phosphate**	1.069g
Potassium Chloride	5.436g
Potassium Sulfate	7.424g
Calcium Chloride	0.221g
Sodium Sulfate	4.144g

Concentrate 3 (10x) - **Humidity Condensate**	Target Wt
Acetic Acid	0.441mL
Benzoic Acid	0.0464g
Benzyl Alcohol	0.259mL

Ethanol	1.506mL
Acetone	0.030mL
Caprolactum	0.191g
Phenol	0.027g
N,N-Dimethylformamide	0.035mL
Ethyl Glycol	0.157mL
Formaldehyde	0.461mL
Formic Acid	0.208mL
Lactic Acid	0.187mL
Methanol	0.218mL
1,2-Propanediol	0.013mL
2-Propanol	0.042mL
Propionic Acid	0.042mL
Urea	0.101g
4-Ethyl Morpholine	0.072mL

Preparing Solid Waste Ersatz:
Mix together double measurements of the following synthetic chemicals to represent solid waste ersatz using durable blender while adding 100 mL of DI water to each batch of measurements (Total DI water: ~150 mL to 200 mL) frequently as it mixes to achieve thick liquid consistency. Measure final ersatz mixture, cover with paraffin and store in fridge.
Wait until you have enough stored reject brine is accumulated from test bag runs (1L or 1000 mL). Dilute solid ersatz mixture with reject brine to achieve appropriate liquid consistency and use funnel to pour in green port side of x-Pack. Make sure air is out of bag before closing. Ready for test runs.

Component	Target Wt
Peanut Oil	20g
Spirulina	30g
Calcium Chloride	30g
Potassium Chloride	40g
Sodium Chloride	40g
Cellulose	15g
Polyethylene glycol	20g
Psyllium	5g
Miso	5g
Dried Biomass	50mg

Calculations regarding Inorganic ingredients:
5g to 100g of in-organics using the formula for 1.8 kg is equal to about 1/18 x the 100g number. Therefore:
40g = 2.22g KCl
40g = 2.22g NaCl
30g = 1.67g Cal2

Experiment Test Bag Procedure:
Applies to all three bags, however for solid waste tests only OA is measured every two hours and recharged with different NaCl concentrations in three to four day increments (i.e. 70, 140, 300 g/L).

1) Label all needed containers
2) Triple Rinse with DI water before, between, and after each test run and/or data point
3) Rinse x-pack with DI water with 1000 ml per side of membrane once at a time and with 500 ml per side simultaneously prior to use
4) 500 ml of DI water put into each side of pack, set aside overnight
5) Locate one 1000 ml volumetric flask, three 100 ml volumetric flasks, three pipettes and rinse three times with DI water
6) Pipette used to measure 100 ml of concentrate 1 into 100 ml flask
7) 100 ml of concentrate 1 was placed into 1000 ml flask (ersatz mix)
8) 100 ml of concentrate 2 and 3 were placed into ersatz mix flask
9) Ersatz flask with concentrates was filled to 1000 ml mark with DI water
10) 70 g/L of NaCl were mixed with 1000 ml of DI water in volumetric flask
11) Before starting run, measure reject and OA measurements using the 250 mL volumetric flask
12) At start time, carefully pour using funnel 500 ml of salt water mixture into the red port
13) Pour 1000 ml ersatz mixture into green port
14) Every two hours, measure green port side of bag using volumetric flask and return samples back to x-pack green port using funnel
15) Calculate flux rate
16) To re-charge salt water, empty red port and refill with 500 mL of (70, 140, 300 g/L) NaCl solution.
17) Hint: Pre-mix NaCl solution for the following test run day
18) At the end of run, pour out what is measured on red port side of bag and re-charge with NaCl solution
19) Rinse all measuring utensils. If bag is not in use for more than 24 hours, place in lab fridge

Results of Experimental Testing

The results of experimental testing are presented in Figures 18 through 25. Figures 18 through 21 present the flux rate of water through the internal membrane of the bag, in units of L/m^2 hr, as a function of time. As shown in figures 18 through 20 the flux rate for wastewater ersatz runs decreases with time due to the concentration of the feed and the dilution of the osmotic agent NACl solution. Also show is that at the bag is reused the flux rate declines slightly due to fouling of the membrane. All three bags performed similarly, with minor exceptions due to experimental issues. Figure 21 shows the same type of data but for the solid waste ersatz. This solution performs in a similar manner to the wastewater ersatz tests except that the initial flux rate is much lower due to the high osmotic potential of the solid waste ersatz.

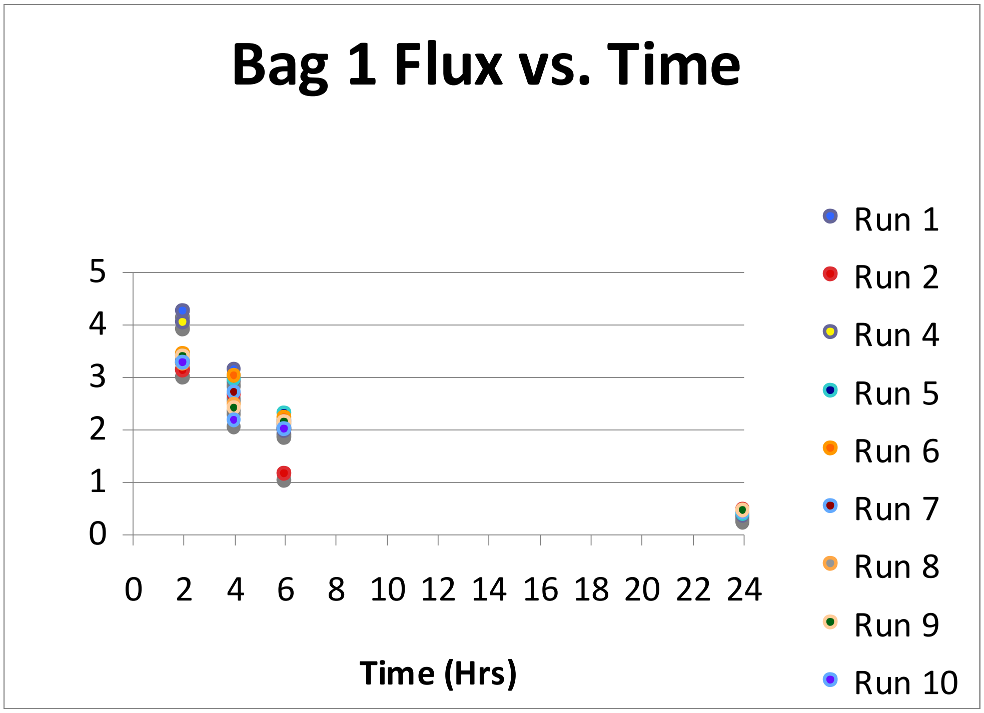


Figure 18. Results of Flux Testing For Bag 1 of 3 Bags Tested

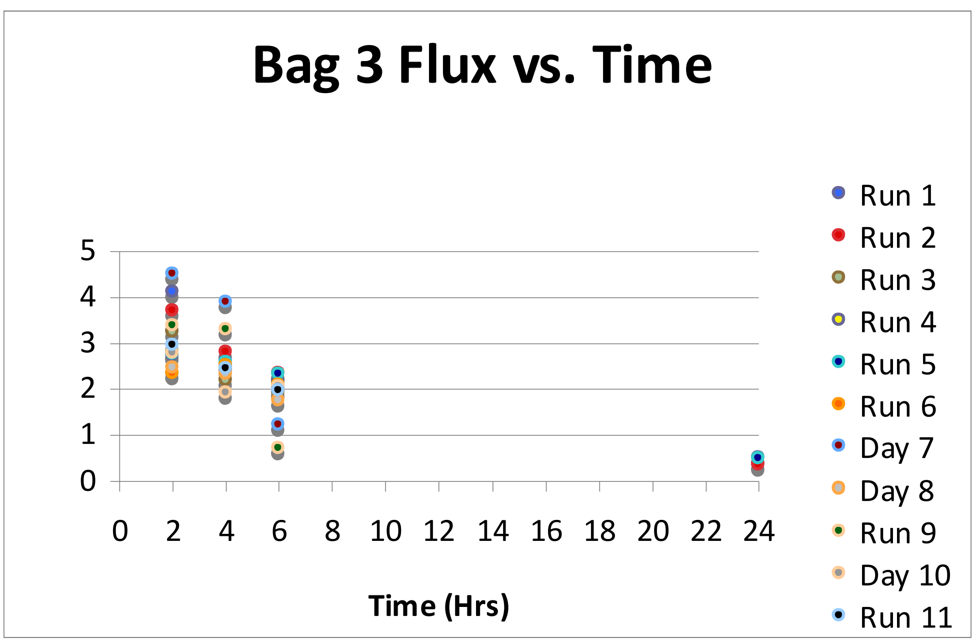


Figure 19 Results of Flux Testing For Bag 2 of 3 Bags Tested

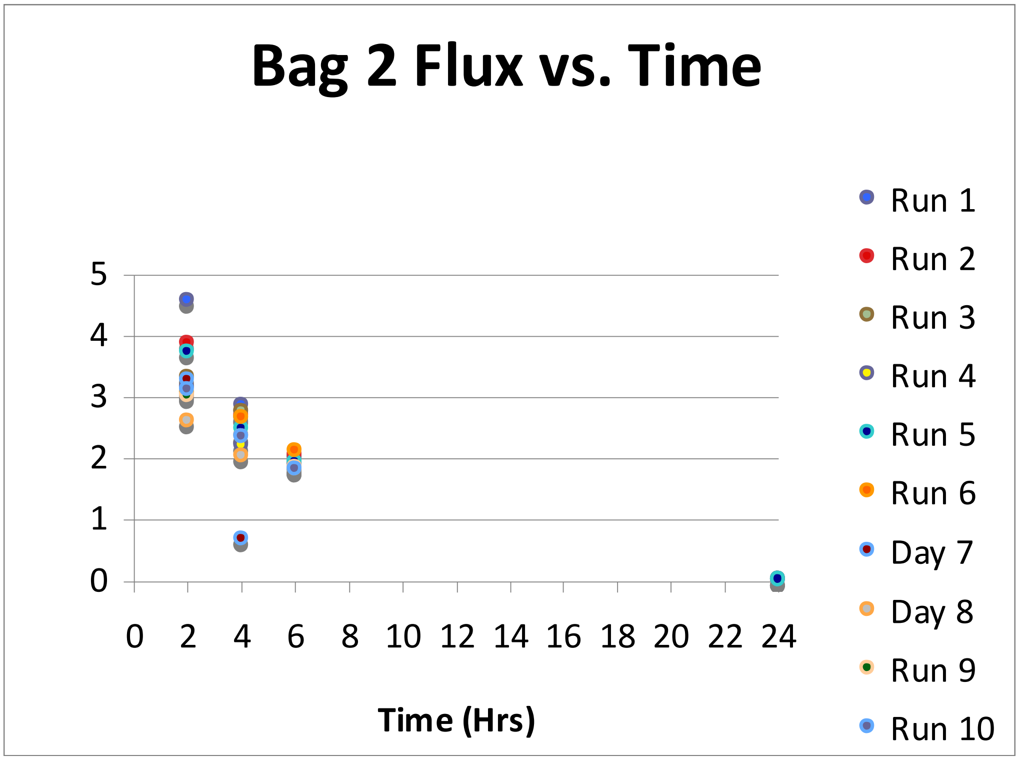


Figure 20 Results of Flux Testing For Bag 3 of 3 Bags

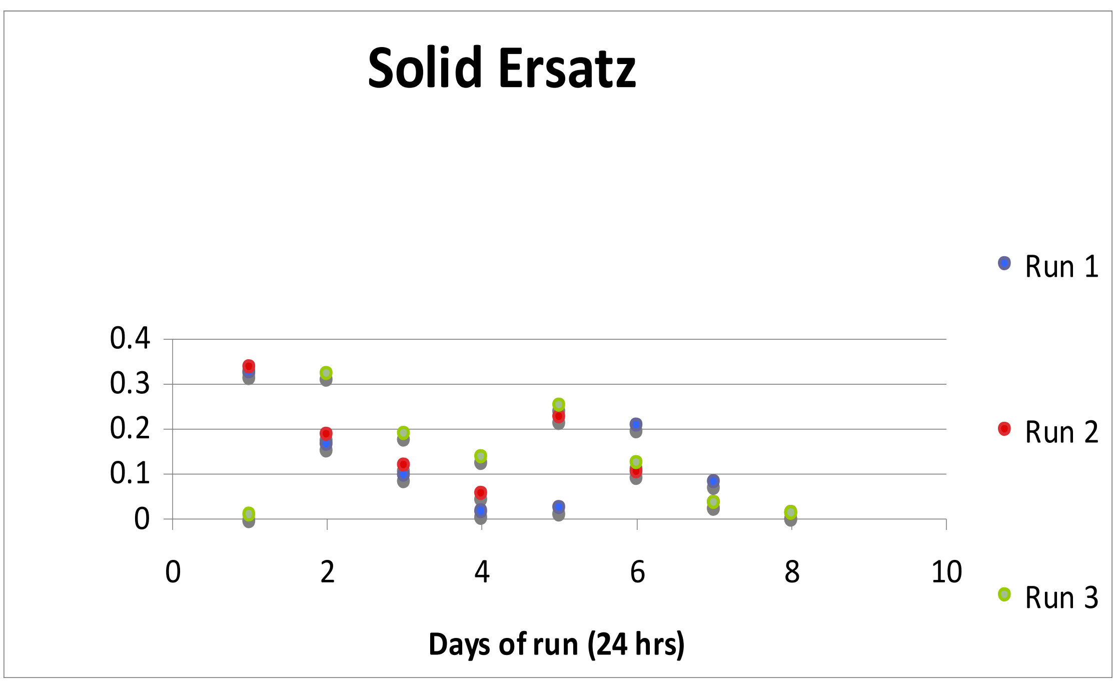


Figure 21 Results of Flux Testing For Solid Ersatz

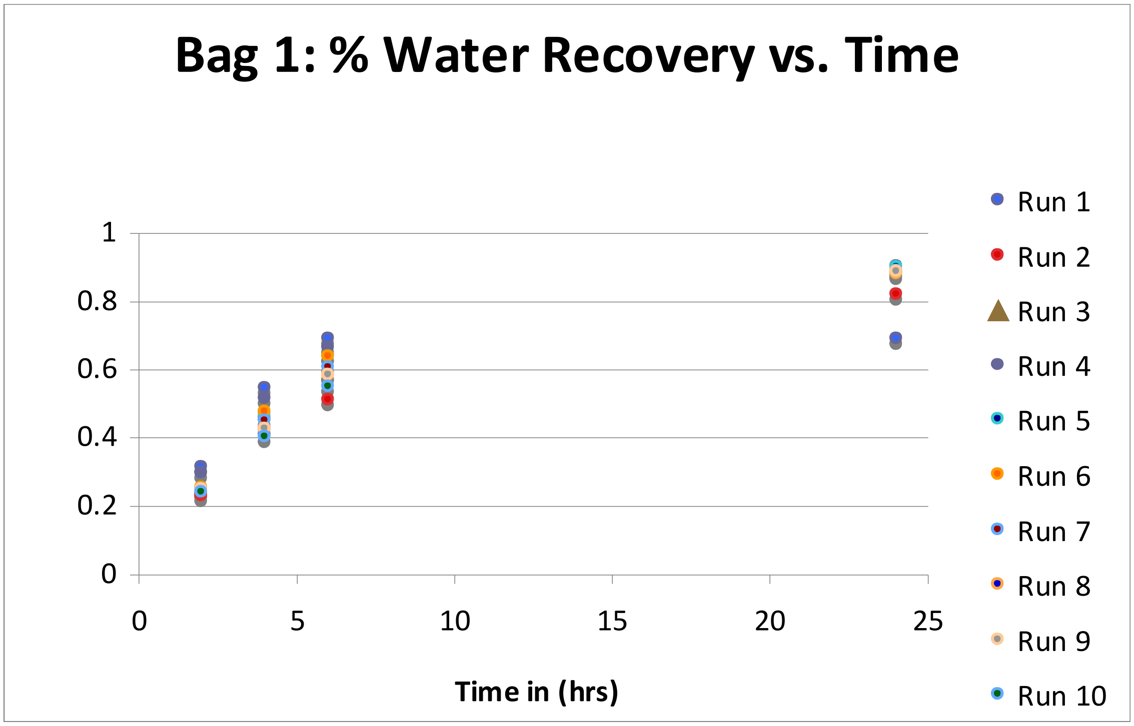


Figure 22 Results of Water Recovery Ratio Testing for Bag 1 of 3

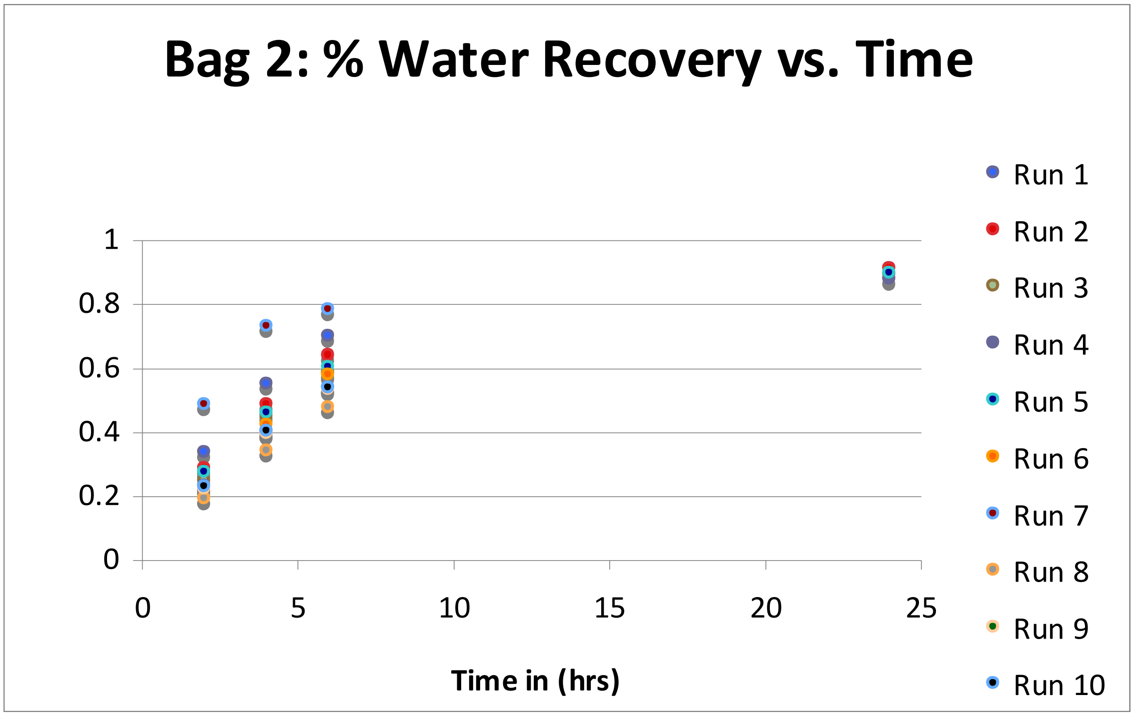
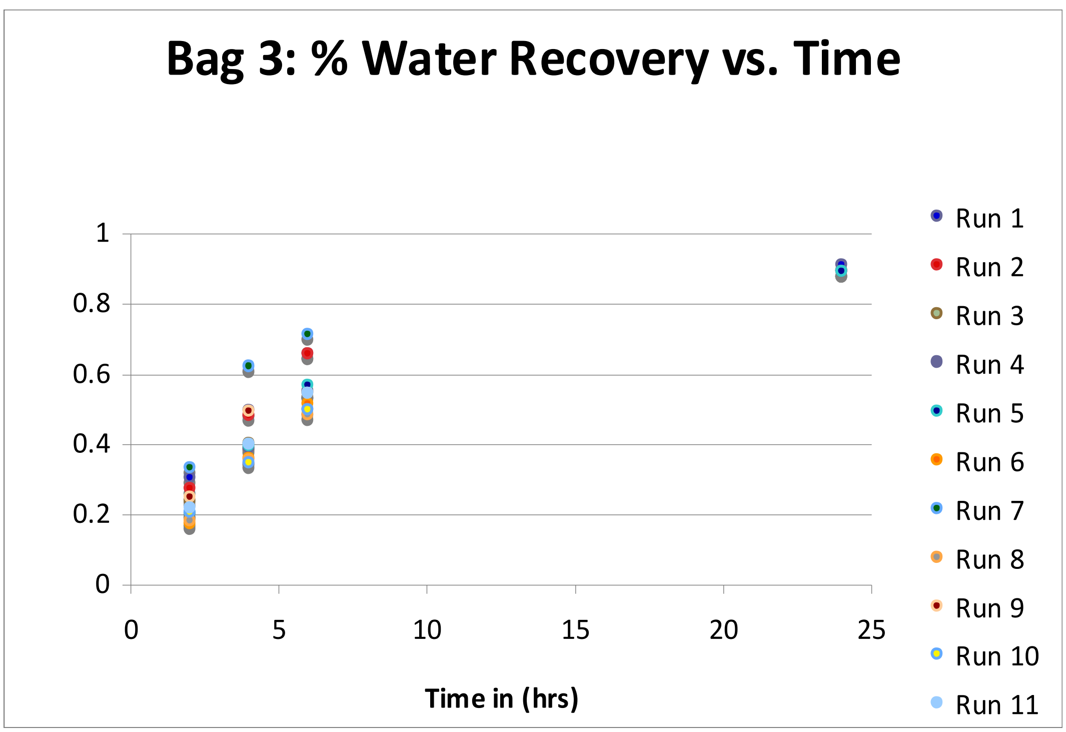


Figure 23 Results of Water Recovery Ratio Testing for Bag 2 of 3



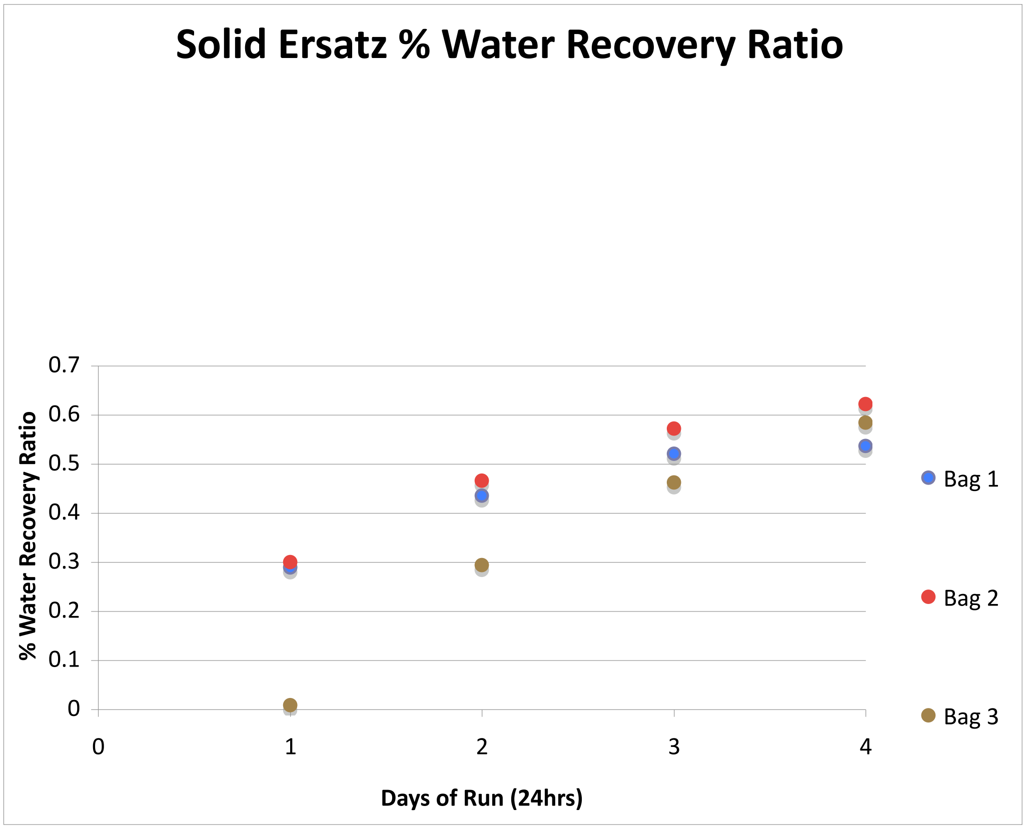


Figure 24 Results of Water Recovery Ratio Testing for Bag 3 of 3

Figure 25 Results of Water Recovery Ratio Testing for Solid Ersatz

Figures 22 through 25 present the results of the water recovery ratio calculations for the same tests presented in Figures 18 through 21. The water recovery ratio is the ratio of the mass of water in the feed to the mass of water produced. Figures 22 through 24 show that the bag achieves a water recovery ratio of approximately 90% after 24 hrs. Figure 25 shows the water recovery ratio for the solid waste ersatz. This shows that after 4 days of contact a recovery ratio of approximately 55% is possible. The combined water recovery ratio is over of 95%.

Conclusions From Experimental Work

The experimental data verifies the assumptions used to size the membrane based water wall for the treatment of spacecraft wastewater. The data is in line with that developed previously from the lightweight contingency water recovery system (LWC-WRS) program. The solid waste dewatering data also support the assumptions used in sizing the membrane water wall. Although additional experimental work will be needed to modify the fit form and function of the proposed system, the work completed herein is in agreement with the calculations used in the preceding sections of this report.

Solids/Residuals Processing in Membrane Walls

Once the wastewater and brine sequestration role of the embedded membrane bag system is fully utilized, the solids sequestration advantages of the bags should be investigated and optimized for advantages over conventional solid waste treatment and disposal systems. This would be the most obvious opportunity to investigate the conversion of wastewater residuals into biologically stable and useful materials. Within this context the treatment strategy and fate of water treatment residuals is highly influenced by the waste stream origin and composition.

Planetary bases, and mature space habitats, will process hygiene water and feces, as well as humidity condensate and urine. These habitats will produce wastewater process solids that will be quite different from short-term transit habitats [10]. This is because these short-term transit habitats will have waste streams that are dominated by urine and humidity condensate wastewater. The composition of planetary wastewater will be larger in volume and contain a large and better metabolically balanced organic dominated solids load. The transit waste will be dominated by the dissolved solids (salts) in urine, be metabolically imbalanced in terms of the carbon to nitrogen ratio, and contain trace toxic organics from condensate. Based on these fundamental differences, both the conversion process and the product fate of these two residual waste streams must be different and are treated separately.

What follows is a rigorous analysis of the digestion mass balances and products for solids handling for both planetary base and transit mission wastewater. This discussion is intended to give a credible theoretical basis for considering the membrane water wall as a wastewater residual solids bioreactor for the conversion of these solids into useful building material within the same physical space (i.e. an embedded FO membrane bag style element). This part of the analysis is based on known wastewater treatment design principles as they would be applied to FO elements at the end of their useful life as water treatment elements. Also, the biological treatment, particularly for the urine dominated transit mission wastewater, may be amenable to purely physical (thermal) or chemical process treatment within the same design envelope, though likely with less optimal results for the final solid product.

However, the real function of this analysis is to give the space system architect the feel for how the processing of solids would work based using off the shelf materials and well understood engineering techniques from established municipal and industrial wastewater treatment engineering. Actual performance will vary based on variations in waste streams (and thus mission assumptions), but the principles of the water wall and its inclusion in system architecture concepts will remain the same.

Thus, the analytical sections to follow should be read as a rigorously presented example, rather than as an exact engineering solution at this time. Also it is good to see the full analysis to get a feel for the probable relative magnitude of product based on mass balance, while showing that those rough comparisons are based on defensible logic rather than poorly supported speculation.

Composted Biosolids for Hydrocarbon Wall Shielding: the Adobe Brick Wall

For hygiene water rich planetary base wastewater, once treatment has moved on from a wall bag the remaining wastewater would be drained and mixed with concentrated biosolids from the feces collection and advanced (secondary) water treatment process (RO salts, spent activated carbon, and biodegradable trash) then reinjected into the imbedded bag for biological treatment. Under proper temperature and pH control these cells would undergo methanogenic composting, thus producing CO_2, CH_4, water vapor, and humus (organic soil). The CO_2 and CH_4 could be harvested for use as habitat makeup gas and water.

It should be noted that the gas resources recovered in this way are not interpreted as potentially large in terms of total volatile mission mass balance requirements like rocket oxidizer/fuel for primary propulsion. This element of the process is mentioned to indicate the possibility of retaining a limited and valuable resource that is a byproduct of the waste stabilization process to balance minor volatile requirements like attitude control and atmospheric leakage.
The conversion of biomass to stable humus would also be a positive product of the waste composting step. The humus would primarily be the product of indigestible organic fiber from the crew's diet. These biosolids are harvested, concentrated in the wall and aerobically processed and/or chemically cured for stability. Then the FO membrane system bags become a hydrocarbon radiation shielding layer, probably with a relatively high residual water content. The FO cell used in this way would have a limited treatment life but would productively harvest the organic wastes in habitat wastewater, thus productively utilizing all soaps and metabolic waste hydrocarbons by embedding them in the habitat wall as permanent radiation shielding humus. These hydrocarbon "dry solids" will contain substantial bound water and thus be a permanent water wall.
Composting accumulation rates should be dictated by the dry mass fraction of the treatment residuals. Total mass balance for a space craft habitat is given in Table 2.

Table 2 Daily mass balance for human life support varies with mission scenario. The following are approximate values based on Wieland [11]. However, mission scenarios range from as low as 2.67 kg/day to as high as 27.58 kg/day.

DAILY INPUTS in kg/day		DAILY OUTPUTS in kg/day	
Oxygen	0.84	Carbon Dioxide	1.00
Food Solids	0.62	Respiration and Perspiration	2.28
Water in Food	1.15	Urine	1.50
Food Prep Water	0.76	Feces Water	0.09
Drink	1.62	Sweat Solids	0.02
Hand/Face	4.09	Urine	0.06

Wash Water		Solids	
Shower Water	2.73	Feces Solids	0.03
Clothes Wash Water	12.50	Hygiene Water	12.58
Dish Wash Water	5.45	Clothes Wash Water	11.90
Metabolized Water	0.35	Clothes Wash Latent Water	0.60
		Food Prep. Latent Water	0.04
Flush Water	0.49	Flush Water	0.50
Totals	30.60		30.60

Examining only the wastewater side of the data and removing laundry water from the waste stream we get the following water and wastewaters solids inputs to the membrane system:

Water (in liters or kg):	
Urine	1.50
Feces water content	0.09
Respiration and perspiration	2.28
Flush water	0.50
Hygiene water	12.58
	____
Total water per crew day	16.95

Volume accumulation of residuals at 95% recovery gives 0.848 L/crewmember day (Table 3). Similarly for solids:

Solids:	
Urine solids	0.062
Sweat solids (into hygiene)	0.02
Feces solids	0.03
Hygiene solids (soap)	0.021
	____
Total	0.133 kg

Or:

133 g/crewmember day

Concentration is given by [12]:

133 g/0.848 L =157 g/L

Table 3 Outputs per crewmember day prior to drying and/or digestion

Water processed	Brine volume accumulated	Solids accumulated (dry weight)

16.95 L	0.848 L	0.133 kg

Hygiene solids are primarily body soap and are not included in Table 2 but are in Table 3. The value used above is extracted from the work of Verostko *et al.,* [10] which functions as the currently available published ersatz for hygiene water. Within this ersatz concentrate mix prescribed for testing, 33 g/L organic solids in a 20X dilution is used. Of this 33 g/L, 30 g/L is soap, with acetic acid, urea, ethanol and lactic acid comprising 90% of the remaining organic solids by mass. This gives:

(33/20)g/L(12.58 L/d) = 20.8 g/crewmember day dry mass of soap dominated organics

Using an organic loading rate of 133 g/L organics is shown to give a mixed – liquor suspended solids (MLSS) loading rate of 156 g/L. Of course actual day to day loadings will probably vary wildly, but this will not effect the stoichiometric or average mass balance associated with treatment, and totals should average fairly close to the values given for long term accumulation based on wastewater design experience.

Conversion process calculations and values for wet activated sludge treatment are well documented [12] [13] [14] for aerobic carbon reduction and nitrification (Stage 1 aerobic treatment), and anaerobic denitrification and methanogenesis (Stage 2 anaerobic treatment).

Detailed stoichiometry and mass balance calculations for the municipal wastewater model are as follows.

Aerated reactors can be expected to remove greater than 80% of the biologically available carbon in wastewater as measured by the total available biological oxygen demand (BOD_L). Biodegradable mass fraction varies substantially but 65% is used in text references for municipal wastewater prior to BOD testing for a specific waste stream. Oxygen to biomass consumption mass ratio is approximately 1.42 mg O_2 req/mg of biomass consumed. This and other values in biomass conversion are generally based on biomass stoichiometry relationships for $C_5H_7O_2N$ [12].

Using these values:

(0.8)(156 g/L)(0.65 BOD fraction)(1.42 O_2 req/mg of bio) = 115.2 gO_2/L residual concentrate stabilized
156 g/L (0.65)(0.8) = 81.1 g/L biomass converted to CO_2
156 g/L - 81.1 g/L = 74.9 g/L biomass retained as sludge

Using the stoichiometric relationship for aerobic biomass conversion [12] [13]:

$$C_5H_7O_2N + 10O_2 \rightarrow 5CO_2 + 2H_2O + NH_3$$

Then:

115.2 ($5CO_2/10O_2$) = 115.2 (220/320) = 79.2 g/L CO_2 production
115.2 ($2H_2O/10O_2$) = 115.2 (36/320) = 12.9 g/L water production
115.2 ($NH_3/10O_2$) = 115.2 (17/320) = 6.1 g/L ammonia nitrogen production

If properly managed the aerobic digestion batch process will also nitrify the ammonia nitrogen [12] [13]:

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

This process should convert the majority of ammonia nitrogen to nitrate nitrogen which is moved on to the anaerobic digestion step (Stage 2) as part of the wet solids rather than becoming a volatile ammonia problem. Please note that the discrepancy in hydrogen between NH_3 in one equation and NH_4^+ is a matter of pH adjustment and is fairly trivial from a mass balance perspective. It tends to be neglected in the available municipal sludge digestion calculation. However, it will probably be supplied by acetogenesis in the wastewater prior to treatment (i.e. the stored wastewater will become acidic and supply the necessary excess H^+). The impact on mass balance in Stage 1 of nitrification is as follows:

$6.1(2O_2/NH_4^+) = 6.1(2(16)/18) = 5.4$ g O_2/L additional O_2 required for denitrification
$6.1(NO_3^-/NH_4^+) = 6.1((14+3(16))/18) = 21.0$ g nitrate/L produced
$6.1(2H^+/NH_4^+) = 6.1(2/18) = 0.7$ g hydrogen produced
$6.1(H_2O/NH_4^+) = 6.1((2+16)/18) = 6.1$ g H_2O produced

This completes the aerobic Stage 1 treatment of the waste solids. Stage 2 to will proceed with denitrification first followed by methanogenesis [12] [13].

$$NO_3^- + 5H_2 + 2H^+ \rightarrow N_2 + 6H_2O$$

21.0 g/L $(5H_2/NO_3^-) = 21.0(5/62) = 1.7$ g/L hydrogen required
$2H^+$ is balanced with the nitrification calculation and is canceled
21.0 g/L $(N_2/NO_3^-) = 21.0(28/62) = 9.5$ g/L nitrogen produced
21.0 g/L $(6H_2O/NO_3^-) = 21.0(18/62) = 6.1$ g/L water produced

74.9 g/L of biosolids is moved forward to the anaerobic composting stage. Methane (CH_4) production rates are calculated based on the remaining 20% of the BOD_L not removed by aerobic digestion [12]. The stoichiometry of the remaining BOD is even more variable and unpredictable than it is for the initial waste stream, but a text reference for municipal sludge digestion [11] uses a 4 to 1 mass ratio as a design estimate prior to specific waste stream testing/analysis. Using this admittedly rough estimation:

156 g/L (0.2)(0.65) = 20.3 g/L BOD_L remains for methanogenesis (any biomass production for denitrification neglected)

This will produce approximately 5 g/L methane, but will proceed through various metabolic pathways simultaneously in a complex organic waste, and will consume a small amount of water as well as convert it variously into H_2, HCO_3^-, CO_2, and intermediate organic products such as acetate. All of the above in some relative proportion will likely occur based on waste stream composition [12]. Although, the gas extracted will be predominantly methane, with a trace of hydrogen and CO_2.

A complete carbon and nitrogen formula is available for municipal wastewater solids [15]:

$$1/50\ C_{10}H_{19}O_3N + 9/25\ H_2O = 9/50\ CO_2 + 1/50\ NH_4^+ + 1/50\ HCO_3^- + H^+ + e^-$$

However, this is not carried through (with O_2) because the difference between municipal wastewater and spacecraft wastewater is significant enough to warrant return to first principles when developing actual observed stoichiometric relationships through testing, rather than referencing normal wastewater engineering parameters.

Complete two stage mass balance per liter of wastewater residuals stabilized is as follows:

Input values per liter:

156 g/L solids input

O_2 requirements 115 g/L (carbon reduction) + 5.4 g/L (denitrification) = 120.4 g/L total aerobic O_2 requirement

Anaerobic denitrification will require 1.7 g/L hydrogen at a minimum but it is likely that the aerobic to anaerobic transition of the bag will be accomplished by purging the O_2 bag with an excess of H_2. For this reason, hydrogen use of 20 g/L or more should be allocated to the process. Mixed hydrogen and methane (with O_2) burning in an attitude control system should be investigated so that combined biogas (methane, nitrogen, hydrogen and trace CO_2) and hydrogen purge gases from the long term anaerobic stage digestion process could be used without further processing

Output values per liter:

74.9 g/L sludge is produced in the aerobic stage with roughly another 5 g/L reduced by methanogenesis. This gives a residual stabilized organic solid recovery of approximately 70 g/L.

Aerobic gas output would be 79.2 g/l CO_2.

Anaerobic gas production would be approximately 9.5 g/L nitrogen mixed with 1.7 g/L hydrogen, hydrogen purge gas as required, and 5 g/L methane and trace CO_2.

Trace water production of 12.9 g/L water during aerobic digestion and 6.1 g/L water during denitrification would also occur but is small compared to the total water still available in the residual concentrate.

From a mass/cost perspective, the oxygen and hydrogen gas inputs and CO_2 gas output represent the primary potential costs, which could make the process uncompetitive with simple disposal of solids and brines. However, the inclusion of algal growth cells in the habitat could recover much of the oxygen and the fate of the gas as fuel indicates that O_2 and H_2 purge though the digesters could be calibrated to match some rocket fuel needs.

Also the humus production approach should be analyzed to determine if it trades favorably in comparison to chemically curing the biomass rather than digesting it. Studying this trade would relate to comparing CO_2, CH_4, water vapor harvest and O_2 required for digestion, as well as digestion temperature and pH control costs vs. the mass delivery costs for chemicals injected for a chemical curing option. The embedded FO bag concept validity is relatively insensitive to how the biomass is biologically stabilized, as long as it is fully stabilized and thus rendered acceptable for human contact should one of the embedded bags be accidentally ruptured.

Therefore, the humus production digester approach relates best to larger more mature habitats with effective O_2 from CO_2 recovery. Nearer term mission habitats will likely follow the transit habitat waste model and a completely different waste processing approach of solids, as well as producing fundamentally different final products and launch mass results.

Urine Solids for Building: the Gypsum Wall Board Wall

Transit mission habitats and other free space habitats will likely continue to be highly constrained in terms of hygiene and other non-drinking water uses. The type of wastewater that is generated in this situation (whether truly an interplanetary transit mission or from a permanent free space habitat) is currently referred to as a transit mission wastewater [10]. This is a wastewater that consists of source separated urine and cabin air humidity control system condensate water, with few if any other inputs. In this scenario, the habitat crew uses sponge baths for hygiene, and feces are not mixed with water and are sealed (and in some cases dried) and disposed of as solid waste. In this model, solid waste other than water treatment residuals from humidity condensate and urine are handled in an entirely separate process. The resulting transit wastewater is therefore dominated by urine salts and urea/ammonia nitrogen with the volatile organic carbon from humidity condensate being a minor constituent by mass, but potentially important from a toxicity perspective.

Urine simulant or ersatz used in testing has high levels of urea (5.2 g/L), ammonium citrate (1.2g/L), sodium chloride (2.3 g/L), potassium sulfate (0.7 g/L), and a number of other salts including magnesium, calcium and carbonate containing simple salts. Digestion in these transit mission bags will require a simple sugar feed to balance the carbon to nitrogen ratio followed by nitrification and denitrification digestion steps [10]. Nitrification is aerobic and will convert all urea and ammonia nitrogen to nitrate nitrogen. Denitrification is strictly anaerobic and will convert nitrate nitrogen to N_2 gas. Operating the bags as two stage batch denitrification reactors should convert the majority of the urea and organics to N_2 and CO_2 with very little residual organic matter. The N_2 and CO_2 produced will be processed by the atmospheric control system and utilized as makeup gas. The remaining wastewater will be primarily a dilute brine.

The Total Dissolved Solids (TDS) used to model the theoretical discussion of urine solids is derived from the accepted ersatz for transit wastewater and is taken from Verostokos et al., [10]. This is recognized as a convenient, and in some ways less than fully representative model that must be verified in process research with actual urine testing in all cases; however, it does allow for basic process chemistry. Mass balance should be less rigorously applied using grams of particular product per liter of wastewater treated than can be done for the planetary wastewater case due to the large variability in urine TDS per volume, but for consistency a similar analysis is presented.

The mass balance for transit brine based residuals will be dominated by NaCl, NH_4^+ (from urea), and $CaCO_3$ with some SO_4^{2-} and miscellaneous additional solids representing less than 10% of the initial TDS value. The other salts and complex organics, while important from a treatment requirement and biological processing perspective, are minor components from an accumulative mass balance perspective.

From a processing perspective, this is a urine dominated wastewater stream that is significantly carbon limited [16]. That is to say it has much more ammonia nitrogen than can be metabolically used given the relative carbon content. For this reason approximately 50% of the required carbon for processing must be provided by additions of methanol and simple sugars. Stoichiometry and mass balance detailed calculations for ammonia dominated stabilization are given as follows.

Initial stabilization of urine based organics is modeled as microbial mediated urea hydrolysis to ammonia due to its relative abundance in comparison to all other organics:

$$2C_6H_{12}O_6 + 2CH_4N_2O + 17O_2 + 30H^+ \leftrightarrow 14CO_2 + 4NH_3 + 20H_2O$$

This metabolism will result in little biomass production in comparison to the inorganic precipitates present and thus biomass is neglected at this point. For every 120 mg/L of urea converted this requires the consumption of 544 mg/L O_2 and gives 68 mg/L NH_3 and 616 mg/L CO_2. Because of the variability of urine this mass balance is not used in favor of the empirically derived wastewater engineering values to follow. What results at this point is a high salt, high ammonia, but low organic carbon concentration wastewater. The ammonia must be converted to nitrate nitrogen (NO_3^-) and then reduced to N_2. Nitrification (NH_4^+ to NO_3^-) is a two step biological process:

Nitrosamonas mediated step [12]:

$$55NH_4^+ + 76O_2 + 109HCO_3^- \Rightarrow C_5H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3$$

Note: $\Rightarrow C_5H_7O_2N$ being the general expression for microbial biomass produced

The *Nitrobacter* mediated step [11]:

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \Rightarrow C_5H_7O_2N + H_2O + 400NO_3^-$$

In actual wastewater treatment plant operations 4.3 mg of O_2 is required to convert 1 mg of NH_4^+ to N_2. No determination is made reguarding how much of that is urea or ammonium as it enters the wastewater treatment plant. 8.64 mg of HCO_3^- (from $CaCO_3$) is consumed in the process resulting in $Ca(OH)_2$ precipitate under correct pH conditions. This will co-precipitate with $CaMg(CO_3)_2$, where natural deposits go by the name dolomite, and $CaSO_4$, which goes by the natural deposit name of gypsum (Note: gypsum is more accurately presented in the hydrated form $Ca[SO_4]\bullet 2H_2O$ and should be recognized for water weight mass balances, but is presented in the anhydrite form for stoichiometric purposes here). These recognizable natural mineral (rock) like predicates will deposit in a matrix of NaCl (halite or rock salt) to form a gypsum wallboard like solid. The dissolution source solid (natural rock) and precipitation solids produced by these four materials, both as mineral interaction with natural waters [17] and as part of industrial water treatment "sweep floc" chemistry [18,19] is extremely well understood and commonly used in the field of environment process engineering. This urine salt derived wallboard filling would be dried in place or removed, sealed within the bag to be dried in forms probably still never being removed from the FO bag.

Solid Stabilization Independent Issues

The digestions presented for both planetary and transit residuals are biologically driven baselines, however, all or part of the feces and garbage could be preprocessed by high temperature thermal processing thus rendering it stable prior to addition to the urine and humidity condensate. In this mode, the wall injected solids would amount to a transit mission wastewater residual in a matrix of charcoal (the charcoal being probably the optimal product of high temperature thermal stabilization in our scenario). This approach should also be tried and a trade study analysis for empirically derived mass energy tradeoffs should be run to determine the right mix of physical and biological processing to optimize the solids to be left in the wall.

A matrix of charcoal and scale salts might undergo a more rapid biological stabilization to drive off the remaining ammonia nitrogen as well as Semi-Volatile Organic Carbon (SVOCs) from the urine residuals and dry it to a superior sheet rock analog in the wall. Only specific waste solids scenario testing will determine the best mix of physical preprocessing of solids residuals (from throughout the habitat) versus. in wall final curing, which is best for any specific solids waste stream. In any case, the final fate of the sterilized semi-dry residuals being in the used and exhausted water wall membrane water treatment bags provides for their curing to final construction appropriate solids, and their permanent sequestration in place as radiation shielding (based on their residual bound water content) and structural support elements.

From this it can be seen that the treatment and sequestration of solids in the water wall is less about embedded treatment, as it is with the water processing stage of the water wall elements, and more about final curing and fate

of the otherwise unrecoverable portion of the solids wastes present in the habitat. In this mode, the solids sequestration really concentrates on removing as much water and volatiles from the solids as possible and then stabilizing and curing them in place as bulk radiation shielding.

The radiation shielding properties of these waste residuals should be investigated and taken into consideration by those qualified in assessing water based particulate radiation protection, as should the potential structural properties of this material as it cures in place. As the waste shell slowly accumulates, is strategically processed, and is cured in place, the used treatment bag may present an architectural and structural option for the evolution of highly protective semi rigid meteorite buffers, as well as permanent radiation shields. The bags at this stage act more as sheet rock and/or adobe brick molds as they do treatment devices. Once the bags are stabilized/cured, they can be removed from the internal pressurized volume of the habitat and used to “sand bag” the exterior. This would allow them to continue their role as radiation shielding and also take on the role of meteorite shielding, while occupying no usable pressurized volume and providing room for new sets of treatment bags internally.

Air Trace Contaminant Control Concepts in Membrane Walls

Once water and residual solids treatment and resource recovery are addressed the final question is what could a flexible embedded membrane systems do in the air treatment mode. Water treatment within the water wall architecture is based on proven technology and methods. Solids processing has not been fully tested using the FO membrane elements, but is presented as a possible follow on use of the FO element using well understood wastewater residuals process engineering principals and methods. Air treatment also is developed in parallel technologies and is analyzed here to give an idea of how future concepts in this area may be pursued and how they might interact with the water treatment and solid waste architecture previously discussed.

CO_2 scrubbing technology is well developed, compact, efficient and fairly sustainable. O_2 regeneration from CO_2 less so but this deficiency has a lesser impact than water from a mission sustainability perspective. Trace contaminant control in air is more of a problem, and the by product gasses, trace toxics and odor producing SVOC from water recovery and solids treatment could make this worse. Thus, a natural progression is to examine if membranous water wall elements could also address habitat air and process gas handling needs as well.

Bio-air scrubbing has been used in industrial air pollution control and most particularly odor control for some time [20]. Models for trace contaminant control can be projected based on these industrial air pollution control systems. However, the technology of gas exchange membranes is also well developed and can be applied in an active way as well. Once water and solids treatment is accepted based on FO membrane architecture, it is logical to investigate the use of hydrophobic (liquid water rejecting) gas permeable membrane elements for use in cabin air treatment and waste treatment process gas. These membranes will pass CO_2, CH_4, NH_3, and O_2, as well as H_2O in the gas phase, but will not allow liquid water to pass.

These membranes have been employed as internal diffusers for CO_2 in algae bioreactors which resemble flexible clear plastic bags with internal gas exchange membranes (Figure 26) and could be used to provide NH_3, CO_2, trace toxics and odor related VOC removal from digester gas prior to the CH_4, O_2, and N_2 exiting through a second gas exchange membrane and a second bag. CO_2 from the digester gas and/or rejected from swing bed CO_2 scrubbers (at the optimal augmentation rate necessary) would provide the algae with the necessary carbon source for photosynthesis.

Mass balance indicates that the algae would be better utilized as trace air constituent control, ammonia removal and utilization, and to scrub the methane supply for a Sabatier reactor, rather than as a primary CO_2 to O_2 recovery device. This is because insufficient bioavailable nitrogen is present to provide for the CO2 metabolism without augmentation and thus re-supply. The water wall algae air scrubber elements are tasked with balancing the solids processing gas production (rather than cabin CO_2) and providing trace contaminant control in the habitat. The algae water walls elements providing these functions are more likely to have reasonable foot prints and power requirements that those required for handling the full habitat CO_2 load (at least initially), and thus may be potentially competitive with more traditional air handling machinery for these trace SVOC functions. Competing with known equipment for converting the bulk of the habitat CO_2 to O_2 is specifically not attempted initially but could develop over time as the system volume increase. Conventional hardware is likely to be difficult to compete with do to the bulk of this mass conversion, however, membrane biological processes are likely to provide value where subtler and more diverse biotransformation of trace organics and ammonia are more important.

One point of clarification on the biology selected. In most cases SVOC and odor scrubbers use "bacteria" not "algae", but most micro-algae used in wastewater treatment are cyanobacteria, so we are really selecting for a microbial community that is both odor control "bacterial turf scrubber" while also having a photosynthetic gas exchange metabolism dominant in the culture. By using conditions that select for cyanobacteria of specific types we get a way to control the bioreactor to use only phototrophic high O_2 algal "bacteria" that we can multi task. In this way a beneficial community is maintained in the SVOC scrubber while potentially developing the future CO_2 scrubber over time. Once said it should be pointed out that the near term use of the algae for SVOCs also minimizes the production of Algae biomass which would also be a draw back of biological CO_2 scrubbing at a larger scale.

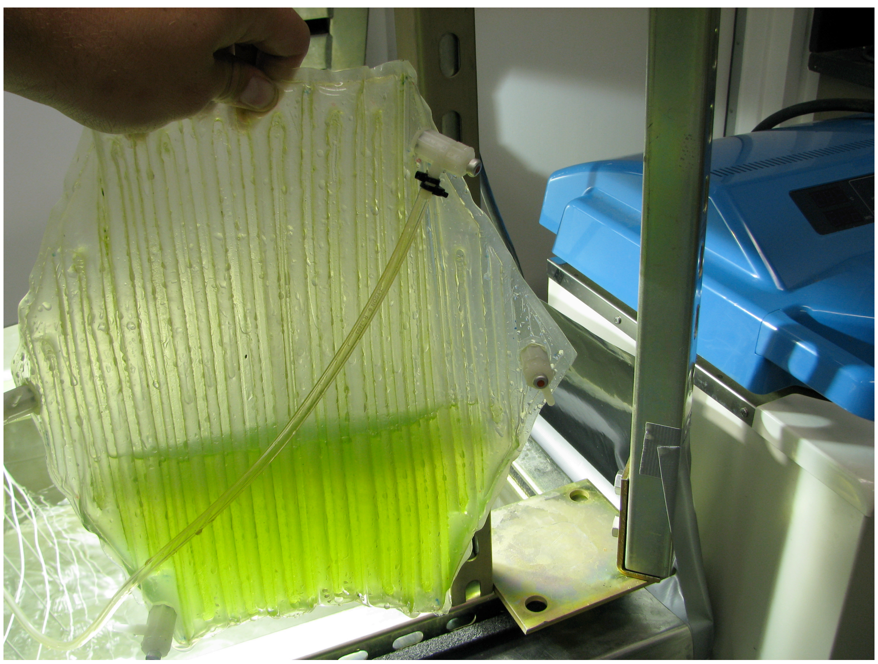


Figure 25 Algae membrane bioreactor developed at NASA Ames for algae bio-fuels research. Note the internal CO_2 gas exchange membrane labyrinth, visible as a clear liner pattern in the bag.

Algae Metabolism Utilization Calculations

Algae metabolism is usually presented based on CO_2, but in fact is more often limited by nitrogen availability, light limitations, and CO_2 bioavailability due to speciation in water. These factors are more important and relevant to the function of the algae metabolism, and thus the design of an algal reactor based air scrubbing water wall element. Perhaps the most important factor to consider is the fact that in most natural algae growth situations nitrogen not carbon (CO_2) is limiting, and this effects basic alga culturing process assumptions because of evolved biology. In addition, as pointed out above, any CO_2 also comes with the production of algae or plant biomass which then becomes a waste problem itself (no free lunch for using biology).

First, we will examine the probable input gas properties followed by the CO_2 versus ammonia mass balance calculations. Using gas for the scrubbing mixture can be of four types based on solids handling assumptions and participation of swing bed CO_2 gas concentrators as a percentage of input gas. In each case it really does not matter if the solids handling is done in the wall as proposed or in more conventional waste processing equipment. If the gas emissions from that waste processing are to be treated and utilized by the habitat rather than being vented, the gas to be processed would have the same composition.

Full mix waste digester gas

A system where a digester is required to accept all wastewater and garbage in the habitat would most likely produce an emission gas stream similar to landfill gas. Landfill gas varies over time based on the percentage of available oxygen in the solid wastes (which is rapidly used up in freshly covered waste) but tends to rapidly approach anaerobic equilibrium. Landfill gas at equilibrium, and thus that assumed for a steady state anaerobic digester processing a similar, garbage dominated, solid waste stream, is 55% CH_4, 40% CO_2, and 5% N_2 [21]. Digesters that are in a transition phase of aerobic digestion prior to going anaerobic will have elevated NH_3 and CO_2. Transition to anaerobic digestion is characterized by low to nonexistent CH_4 production, slightly higher CO_2 production and a transient spike in H_2 production. So the gas emissions from operating a mixed waste digestion process will follow the 55%-40%-5% brake-down, with process inefficiencies possibly driving the CO_2 to CH_4 ratio closer to equal, and possibly allowing trace H_2 and NH_3 emissions to come through.

This actually provides a reasonably good feed gas for a Sabatier reactor, but provides little nitrogen support to an algae air scrubber. In this case, the cabin CO_2 and ammonia gas from a urine tank degasser might be used as the primary feed gas streams to grow stable algae cultures, with the cabin air being scrubbed by mature microbial (probably cyanobacteria) cultures on a cyclical basis. In this mode the algae bioreactor would run on light and cabin air for most of the time, as a cabin air algae turf scrubber for VOC and trace toxic organic air pollutants, but periodically being transitioned to ammonia nitrogen rich waste gasses for a period of time to boost biomass. However, a more stable and optimal approach might be to use these bags for digester gas scrubbing as the primary function of the algae water wall. This is because the amount of CO_2 to NH_3 might be closer to equal for the algae's metabolic needs, and the NH_3 and VOC scrubbed CO_2 and CH_4 output would provide a near balanced Sabtier input.

Wastewater solids only

As shown by the aerobic output gas stage calculation in the solids handling section, the CO_2 to NH_3 production ratio is 80:6 by weight. This gives a C to N ratio of 22:5 or about 4.5:1. Optimal C:N is 105:15 or about 7:1 for algae [12]. This indicates that full utilization of NH_3 would be archived but only if additional CO_2 was provided by the air revitalization system. However, it is likely that a substantial amount of this ammonia would be nitrified (converted to NO_3^-) and retained by the solids and eventually reduced by anaerobic digestion to N_2. If this percentage is near half (as it generally is noted to be in wastewater effluent testing) [12] then the off gassing CO_2 would be in near perfect balance with the nitrogen uptake needs of the algae and both should be nearly fully utilized (theoretically at least).

SVOC scrubbing should be similar to the mixed waste example given earlier. However, if wastewater solids digestion is pursued, the odor control function of the algae is likely much more critical than in thermal processing or mixed waste composting. In both the mixed waste composting and the wastewater digestion only models there is quite a lot of gas exchange and mass balance components to account for and it is likely that these gasses and odor SVOC will be difficult to control. This is indicated by the complexity analysis in this area and somewhat imprecise results. Biological process of this kind will be sensitive to system upset and very wildly based on waste stream input. The primary advantage to biologic solids handing whether in water wall bags or in a more traditional digester apparatus, prior to stable solids injection into the spent bag element, is the production of methane.

Methane production is enabled by biological processes and is advantageous for capturing hydrogen for Sabatier reactions for the recovery of oxygen from CO_2. However, it must be traded against the simplification and volumetric advantages of traditional physical (thermal) or chemical processing of solid wastes. Biological processes are not necessarily advantageous for bulk mass balance conversion of solids and gases, but methane production may be the one salient advantage. Biological processes involving algae have represented both qualitative and quantitative advantages for odor (SVOC) and trace toxic air containment issues in the gas phase. This indicates that unless methane production is highly prized by the system engineers, it is likely that primary (first stage) water treatment and air trace scrubbing will be the roles of the water wall membrane elements, with solids stabilization primarily occurring out side the gas (with the exception of the urine associated high ammonia nitrogen transit mission residuals).

Transit only (probably with thermally pre-stabilized solids)

Paradoxically the transit mission residuals only digestion, with its ultra-high ammonia nitrogen content, actually may be optimal for algae as a feed gas water wall scrubber. This indicates that urine tank off gas (with or without the water wall urine treatment) would benefit from an algal ammonia nitrogen and SVOC treatment provided by the algal gas treatment elements.

This gas would follow the pattern for initial aerobic degradation of urea given previously. Every 120 mg/L of urea converted the consumption of 544 mg/L O_2 is required and this gives 68 mg/L NH_3 and 616 mg/L CO_2. Urea content for urine is modeled at approximately 2.5 g/L [10], and is by far the single most dominant organic component. This would indicate 2500 mg/L urea, which is a bit high based on laboratory observations (during LWC-WRS testing) but can work as a worst case benchmark. If we assume about a 50/50 dilution rate with humidity condensate transit water, this gives a urea content on the order of 1250 mg/L in the waste stream. This is roughly 10 times the normal treatment concentrations in wastewater treatment, but if properly metabolically balanced should follow a similar mass balance. This gives a demand of 5440 mg/L O_2 and gives 680 mg/L NH_3 and 6160 mg/L CO_2.

This indicates that (again regardless for whether the water wall bags are used to concentrate the urine brine) the urine dominated transit wastewater brines/solids will be stabilized by driving off ammonia and carbon dioxide at about a 10:1 ratio in cabin (aerobic) air. In addition, this is true whether this is done biologically or physically, and regardless of if it occurs in a wall embedded bag or in any other reactor and/or brine drier. Thus any transit mission brine dewatering, and the transit mission water treatment and processing of solids are the operative assumption as well. If the other solids are to be included in the wall material they are likely stabilization, utilization, and/or storage method will produce this gas, and it is this gas that is logical to design for. This assumption also effects solid handing in that thermal stabilization of garbage and human solid waste is probably the operative assumption, best added as thermally treated charcoal after the urine and humidity condensate (transit mission) water treatment and stabilization of solids has already occurred.

Swing bed gas introduction

Swing beds CO_2 scrubbers produce an excellent CO_2 carbon source for algae air scrubbing units if necessary, but likely would do so in an excessive over abundance if used as the primary CO_2 to O_2 recovery device. However, the swing bed is sensitive to ammonia and other SVOCs. An optimal architecture likely includes bio-scrubbing of waste processing air and a percentage of cabin air (say 5%) per pass, prior to that air being dried and passed through the swing bed reactor. In this way the bio-air scrubbing would work to compliment and protect the highly mass balance effective CO_2 conversion technology by removing ammonia and VOC from the process air.

Though algae has been proposed for oxygen regeneration it would require large inputs of ammonia nitrogen and carry a larger ESM foot print to do this job. Looking at the nitrogen mass balance alone it is likely that the oxygen regeneration role will be hard to justify. An ammonia and trace gas control role seems much more promising.

Sizing Calculations for Water Wall Membranes

Basic light reaction and mass balance for CO_2

The basic light and mass balance reactions are well understood for algae. Photosynthesis is given as follows:

$$2H_2O + CO_2 \rightarrow CH_2O + O_2 + H_2O$$

$$\Delta G \approx +\ 115\ \text{kcal/mol}^{-1}$$

CH_2O represents the carbohydrate associated with biomass. The reverse of this reaction is respiration:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

$$\Delta G \approx -\ 686\ \text{kcal/mol}^{-1}$$

Or slightly less than 6 times the above (115 X 6 = 690). Functionally this is a two step energy capture and convertion process given by [22]:

$H_2O + NADP^+ + ADP + Pi \rightarrow O_2 + ATP + NADP$ (light harvesting reaction)

$CO_2 + NADPH + H^+ + ATP \rightarrow CH_2O + NADP^+ H_2O + ADP + Pi$ (The light-independent reaction)

Nitrogen mass balance and other factors
Ammonia nitrogen is a more interesting proposition. Urine in transit mission waste and the concentrated ammonia nitrogen loading of all habitat wastewater streams indicates that vapors containing large amounts of ammonia are a particular concern. The limiting nutrient in most if not all growth scenarios for algae is bioavailable nitrogen [22]. Nitrogen in the form of ammonia is bioavailable for algae. The C:P:N ratio for algae is 105:1:15 [12]. This indicates that stable algae biomass can uptake a substantial amount of nitrogen and fix it for later thermal stabilization. At the same time small to mid-sized trace organic contaminants (VOC and/or toxic trace organics) would be dissolved in or by water and then absorbed by the biomass and also sequestered for thermal processing as well.

Preliminary Alternative Physiochemical Concepts to Air Treatment

This section contains a rough outline of an alternative approach to atmosphere treatment using the membrane water wall that does not require the use of algae. It is provided only for discussion as very little work has been done to flush out the concepts.

Air treatment in a spacecraft is traditionally composed of the functions of thermal control, humidity control, CO2 control, and trace contaminate control. All of these functions can be accomplished to some extent by contacting cabin air with a water wall element constructed with a hydrophobic gas permeable membrane. Such a water wall element would be separate from a water/solids treatment wall element described in the proceeding sections.

The air treatment element membrane would be in direct contact with the spacecraft atmosphere and would be designed to maintain an equilibrium in the atmosphere that maintains humidity, CO2, and semi-volatile organics within space craft allowable maximum concentrations. Volatile organics would still have to be addressed using traditional thermal or UV catalytic means. The following sections describe how such as system would perform such functions.

Humidity Control

Humidity control is commonly accomplished in a space craft by the use of a condensing heat exchanger. A condensing heat exchanger operates by reducing the dew point of a gas such that water vapor condenses and the resulting gas achieves a targeted relative humidity. A number of researchers have bee looking at the use of membrane condensers to achieve such control (ref). An alternative approach is to modify the osmotic potential of a water layer across a hydrophilic membrane to cause water vapor to condense.

The approach proposed for use in the water wall is a combination of both thermal and osmotic differences. Osmotic pressure differences are used to control latent energy, condense water out of the atmosphere and thermal control is used to control sensible energy and maintain the cabin air at a specific temperature. In this process water on one side of a membrane is maintained at a specified temperature and the osmotic potential is adjusted to condense water out of the air, which is in contact with the other side of the membrane. The liquid water is then treated in a desalination system and returned to the water wall at the appropriate temperature and osmotic potential to repeat the process in a continuous cycle. The water removed in the desalination system is recycled to potable water standards after post treatment to remove any residual semi volatile compounds and biological contamination.

CO_2 Control

CO_2 is sparingly soluble in water. However, once solubilized, CO_2 can be converted to carbonic acid, depending on the solution pH, or adsorbed by liquid amines or other liquid or particulate adsorbent materials. Thus a water/membrane, gas construction can be used to strip CO_2 from cabin air as long as the carbonate ions are removed at a rate in proportion to the generation rate and solubility restricted diffusion rate of CO_2 which requires some pH control. They key to such a process is to provide enough gas/liquid contact area to address the low solubility and diffusion limits of CO_2 in water. The membrane water wall provides an ideal construction for such an interface.

Trace Contaminate Control

The levels of semi-volatile compounds in a space craft atmosphere can be controlled by contacting it with liquid water. In such a construct the maximum level of a given semi-volatile compound in the atmosphere can be calculated by the Henry's Law constant associated with the compound. If the liquid concentration of the compound is kept low by processing the compound through a catalytic reactor or adsorbent bed this disequilibrium between the liquid phase and gas phase will strip organics from the atmosphere.
A membrane water wall that provides a hydrophilic gas transfer membrane that contacts the atmosphere with sufficient surface area of water and then further processes this water to remove any soluble or semi-volatile compounds will thus act as an air scrubber.

ACTIVE AND EVOLVING MEMBRANE WALLS IN PRACTICE

The Active and Evolving Membrane Wall

To this point the focus has been water treatment and residual solids conversion/stabilization as well as air treatment, but one should also consider the benefits of the membrane water wall recovered resources in long term habitat structure development. This approach provides for growth of transit and planetary base architectures through the byproducts of habitation. More specifically, it does this through the application of urine solids such as halite, gypsum, and dolomite as well as hygiene solids sequestered as composting generated humus.

The first application of water treatment residuals accumulated by embedded membrane treatment should be to simply leave them in the walls as a water wall radiation shield until more advanced materials processing is warranted. This has been mentioned in the processing discussion as a primary beneficial fate of the wastewater solids, but requires a more complete justification.

Water and/or hydrocarbons have long been recognized as excellent radiation shielding [23], but have not been applied primarily because the mass (particularly of water) necessary to provide this shielding has been considered prohibitive from a launch mass/cost perspective. Water or hydrocarbons are superior to metal in that they tend to absorb cosmic ray radiation, which is high mass particulate radiation, without secondary nuclear partial showering effects that are generated by metal shields. In operations and planning, waste and down mass is considered a necessary sanitary expense rather than an unacceptable waste of up mass investment. However, one could ask, if water or hydrocarbon is an inherently superior shielding in the deep space environment, how can a water wall be too much of an up mass investment while water treatment residuals are vented or down mass? It would be a much better use of resources to permanently sequester all residual solids, as well as all water treatment brines and hydrocarbon solid wastes as permanent shielding material. In this way large and robust radiation protection layer could be developed with minimal additional launch mass.

The accumulation of treatment residuals in the wall following the treatment process life of the membrane wall bag moves the membrane wall from the water treatment role into the resource mass harvesting, stabilization, and sequestration role. Harvest of waste mass and doing away with down mass and/or on site contamination through further processing of water treatment residuals then becomes the primary immediate payback from a launch mass versus return value perspective. In this role human habitation becomes a resource producer rather than a sunken mass cost.

Thus any contaminated wastewater treatment residual is potentially a future space habitat building material if stabilized and stored away from the crew. One can envision this residual wastewater as the inflation and shielding working fluid for the inflatable habitat and structure of deep spacecraft. This approach would allow larger spacecraft structures to be packed as lightweight, small volume inflatable elements for launch and then pressurized to their final form in orbit using recovered wastewater. In this mode, the residual water would never reenter the habitat volume and/or areas that have the potential of contacting the crew, but would still provide structural rigidity (by providing an incompressible fluid inflation material) and what is recognized as a superior particulate radiation shield without further processing.

Better solids recovery and targeted processing offers even more sophisticated uses for waste residuals. In long-term and stable habitation scenarios, with a large amount of hygiene water solids, solids should be concentrated and composted as described earlier. This compost can remain as hydrocarbon shielding and/or as brick wall, or can become soils of plant systems in planetary applications. Urine and humidity condensate will be dominated by urine salts and scalenets (i.e. calcium and magnesium based solids). Experiments into gypsum like building panel material should be considered particularly for transit mission wastes from space stations and continuously cycling transit craft (referred to as cycling ships often proposed for a developed Earth-Mars transit architecture). The chemistry and process development of converting urine salt waste stream material into usable halite (NaCl), gypsum ($CaSO_4 \bullet 2H_2O$), and dolomite ($CaMg(CO_3)_2$) dominated construction materials seems promising based on the prior discussion on the processing of solids.

Increasing crew safety, habitability, and mission stability through a full resource recycle philosophy in space design is achieved by applying wastewater treatment brines as a local building material. In simple terms it allows for the allocation of cheap bulk shielding materials even in space habitats in orbit, where no *in situ* resource materials are at hand. This in turn could increase the size and robustness of space architecture at little or no additional mass delivery related cost. With enough residual accumulation time, much larger and more robust space craft habitats and structures can be developed with residual brines providing the bulk of the system mass and toughness.

On a more strategic and philosophical note, earlier attempts at closed ecological life support (CELSS) have failed to fully develop, primarily due to Earth agriculture based models conflicting with real ESM priorities. The membrane water wall would allow the development of full resource utilization and the introduction of biological elements in a space operational environment in an appropriate and more effective way. Life and habitat evolve to exploit opportunities presented by available resources rather than habitats being developed to match the needs of assumed plant and animal participants. This is achieved by allowing the habitat architecture to apply physical and biological process principles at the small scale and within the structure first, as is done by using the membrane treatment wall system.

A Practical Near-Term Operational Approach to Developing a Water Wall

A practical near-term building block approach to developing the water wall is provided by the incorporation of the FO membrane bag directly into the construction of the Cargo Transfer Bags (CTBs) and then using the CTBs as proposed by Howe et al [24] to provide flexible habitat building units. In this mode the membrane elements embedded in the CTBs could be added to the habitat structure as building elements and then networked to provide fluid treatment, eventually ending up as stable permanent wall construction elements. Teaming the water wall concept with those being developing for CTB reuse would provide a unique synergy and represent a truly advanced life cycle reuse option for the CTBs.

The first step in the process is to develop a CTB envelope with the FO bag incorporated into the layers of the CTB. The function of the membrane bag is completely insensitive to the outer bag construction, so the CTB outer skin (being waterproof) can function as the outer envelope of the FO bag. The CTA FO membrane bag is simply fashioned into an insert and pleated directly into the CTB bag wall. The whole CTB them becomes an FO water treatment bag, when it is done with its primary role of transporting crew stores. In this way the CTBs, rather than becoming garbage become building blocks of the life support water recycle system, while also become building elements of the habitat itself as described by Howe et al., [24].

To understand what this would look like we borrow Figures 26, 27, and 28 from Howe et al [24] for illustration

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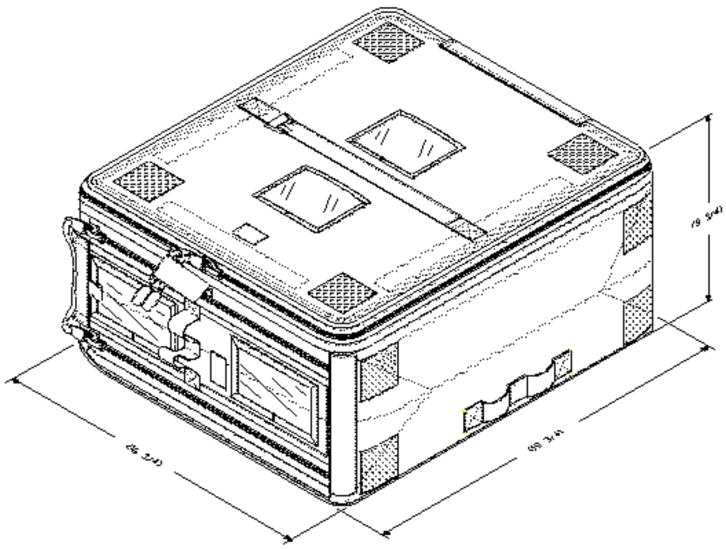

Figure 26 A standard Cargo Transfer Bag (CTB).

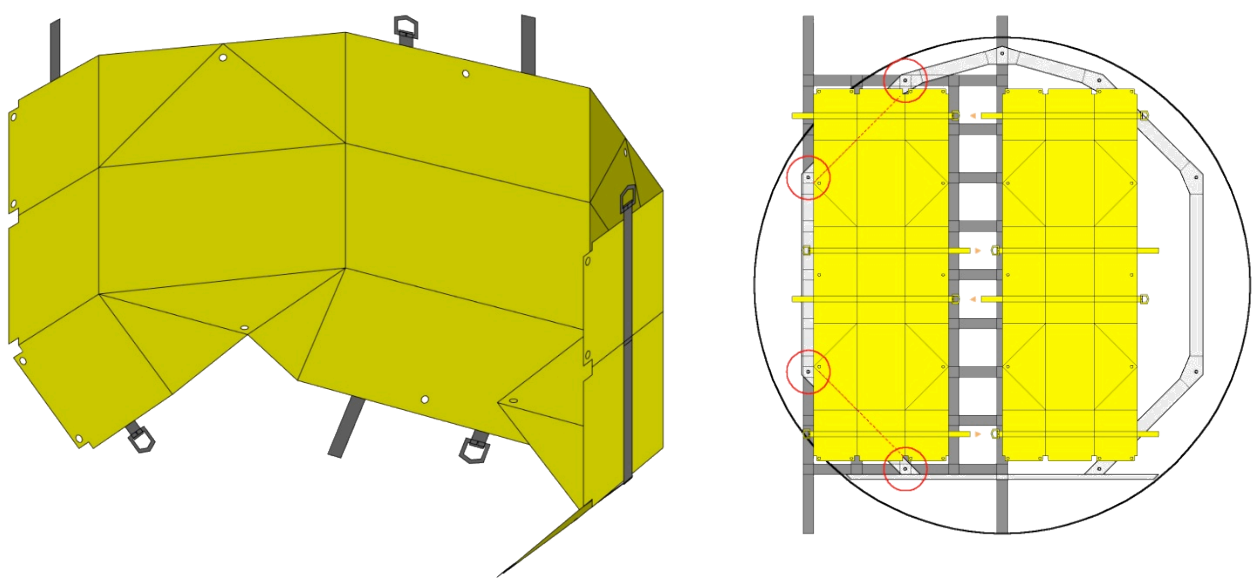

Figure 27 CTB unfolding.

Figure 28 Unfolded CTBs incorporated into wall elements (LSSP Habitation Team).

Once the CTBs are unfolded and mounted as shown, the X-Pack FO bag based CTBs could provide a pretreatment of any other water treatment system, thus increasing mission reliability over time while they are in use as wall elements. Over time the accumulated CTBs become an ever increasing life support and radiation shielding capability based of what is now garbage (the CTBs) and wastewater treatment residuals (cured material inside).

Higher Level Design Consideration

The primary drivers for early adoption of the membrane water wall are the need to provide low launch mass water recycling; this is followed by starting the sequestering of waste products sooner rather than later, and finally the sequestration of material as stable low cost building material rather than simply waste. Current handling of waste on the International Space Station (ISS) is potentially neglecting substantial material assets. This has both technical and programmatic implications. If the evolution of habitat systems is in the direction of 100% resource utilization and reuse, there is an immediate need to look hard at every time water is vented, trash is de-orbited, or a treatment residual is designated and handled as a waste product.

Space systems have traditionally depended on high levels of one-time use expendable materials. Taking a full materials recycle experiment approach in space habitat design will increase stability, safety, and research relevance of human presence in space to environmental sciences and engineering. In doing so it will increase the credibility of near term human space activities as an exercise in learning how to live and work in space in a way relevant to future longer transit distances and longer stay time space activities.

This is not meant to be critical of current operational priorities. However, it is meant to suggest that if ISS and other human space systems are to teach us how to live and work in space we should make them truly an experiment in sustainable and healthy habitat design and long-term habitation, rather than this design consideration being a sidelight to other mission priorities. A new and advanced approach to developing biological systems inspired spacecraft design, starting with a membrane ELS based habitat envelope structure, and moving in the direction of substantially greater mass retention, is a logical step in the right direction.

Both current mechanical and/or physical chemical unit process based systems, as well as first generation vascular plant based Closed Ecological Life Support (CELSS), are severely limited because they are not reorganized at the substrate level and are not able to evolve into completely new and unexpected shapes dictated by the space operations environment. For this reason, they cannot breakthrough current limitations in ELS performance. The membrane water wall concept is completely reorganized at the basic construction material level (analogous to tissue level in a living system) and thus is free to breakthrough current life support concept limits entirely.

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