Membrane Based Habitat Wall Architectures for Life Support and Evolving Structures

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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 life support materials recycle, particularly air and water. This study proposes a system for membrane based water, solids and air treatment functions that is embedded into the walls of inflatable habitat structures to 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 finally become a permanent structural element for the mature habitat shell. Secondary air treatment membrane elements similarly located are also briefly considered as potential future additions to the treatment architecture. The technology used is not speculative but is based on established emergency water recovery technology being used in the Light Weight Contingency – Water Recovery Apparatus (LWC-WRS), Direct Osmotic Concentration (DOC) but in a scaled up version. As such all hardware proposed is based on commercial off the shelf products and materials, and the 1st stage water treatment is well demonstrated and documentation indicates better than 90% water recovery as a first stage treatment for hygiene water and urine. Thus, the proposed technology is based upon proven engineering solutions that will be analytically demonstrated to potently serve a much larger role in future space architecture. In addition it should be noted that the concept of using a water wall for thermal and radiation shielding is the current baseline assumption for planetary base habitats and rovers.

Nomenclature

A_c	=	The membrane flux resistant constant in (l/m^2 hr atm)
CELSS	=	Closed Ecological Life Support
DOC	=	Direct Osmotic Concentration

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ELS	=	Exploration Life Support (i.e. Experimental Space Life Support at NASA)
FO	=	Forward Osmosis
F_w	=	Total water flow across the membrane in (l/m^2 hr)
ISS	=	International Space Station
LWC-WRS	=	Light Weight Contingency – Water Recovery System
MF	=	Micro-Filtration
ΔP	=	Hydrostatic pressure (atm)
$\Delta\pi$	=	Opposing osmotic pressure potential (atm)
RO	=	Reverse Osmosis
TDS	=	Total Dissolved Solids

Definitions

Water Recycle: The processes by which wastewater is treated for beneficial reuse
Waste Stream: A class of liquid or solids waste based on its general composition and relation to other similar waste generally coming from the same or similar process origins

I. Introduction

Wall membrane based Exploration Life Support (ELS) is presented as a family of advanced concepts for reorganizing habitat water, air and solid waste processing, as well as architecture and materials construction. The goal is for life support to stop being a set of machines (separate from the habitat itself) and become an integral part of the structure of the habitat. Also, this concept utilizes waste products completely and converts them into resource assets not currently available due to launch mass constraints. In form, the Water Wall is basically a plastic bag system with internal membranes that are embedded into the wall of the habitat. There it processes primary wastewater, and collects and permanently sequesters concentrated brines and biosolids, stabilizing them and converts them into building materials.

The first potential benefit of using membrane based wall embedded water, air, and solid waste treatment and resource recovery is the potential for near zero footprint ELS. Currently all water and air recovery, recycle, and contaminant control is done within traditional process equipment. This equipment takes the form of mechanical equipment racks within the otherwise useful habitat volume. This type of system, like all mechanical equipment, requires power, cooling load energy, periodic maintenance and sophisticated autonomous controls. All of this dictates that life support competes for (and limits) useful habitat volume, and thus contributes substantially to the total system life cycle launch mass required to provide life support for a mission.

Another aspect of current mechanical and/or physical chemical water and air treatment processes used in ELS is that a substantial amount of water and/or oxygen are trapped along with the contaminants (as the residual water content remaining in concentrated waste brines) when they are removed and become waste. This material must be disposed of at considerable cost, and is a total loss in terms of habitat resources. It would be much wiser to use a membrane based wall system to utilize these waste materials within an evolving structural and shielding layer, through human waste based *in situ* resource utilization. Using a model that includes active membrane walls and evolving habitat construction through the use of biosolids and brines as permanent wall structures, these materials can potentially be leveraged to provide revolutionary new directions in habitat design. Where previously space system designs were limited by the inability to afford to deliver lower grade bulk building materials at an acceptable cost, now one can create bulk building materials from waste materials.

The value of the residual material would be assessed based on composition and desired function. For example dry urine solids would be similar to gypsum wall board filling. But wet, 95% to 99% water recovered urine solids would be treated as residual water, potentially for radiation shielding. In the latter case, a specialist in radiation shielding design would be consulted to determine optimal thickness of the final layer and the process volumes would be adjusted accordingly, but process design principle would be little affected. It should be noted that 99% water recovered urine is still more than 50% water by weight as are all solids in this study, so radiation shielding should be assessed as water equivalent by thickness.

II. Water Process within a Membrane Based Wall Structure

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 (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 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 that does not apply to other membrane applications.

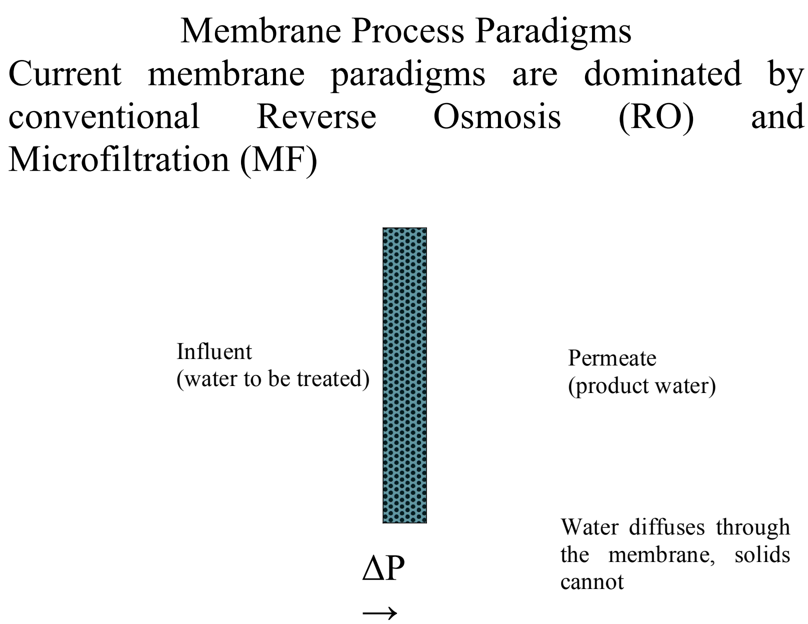


Figure 1 Current membrane paradigm requiring pressure containment

Membrane systems that employ different driving forces such as forward osmosis (FO) or vapor transport (i.e. membrane distillation and/or osmotic distillation) [1], 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 [2] (Figure 2). This process is generally followed by reconcentration of the receiving brine by conventional RO.

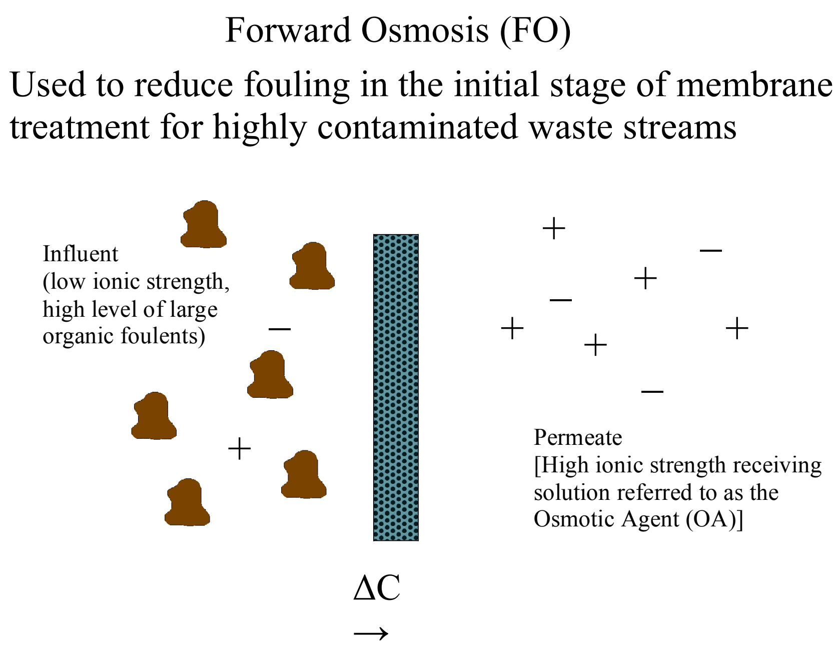


Figure 2 FO process explanation; Note that ΔC is the concentration gradient rather than ΔP which was the hydrostatic pressure difference.

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:

$F_w = A_c (\Delta P - \Delta\pi)$ 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 (Eq. 2) to read:

$F_w = A_c\ \Delta\pi$ 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 water walls.

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 near to balanced (i.e. ΔP still zero across the membrane). In this situation the hydrostatic pressure could be in either 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 be in the 5 g/L as NaCl range based on FO research experience[2]. In a flexible membrane bag inside a flexible external plastic bag envelope construction arrangement this 58 psi is acting on the membrane [4] at the microscopic level and results in a pressure equalizing flux of water across the membrane. But, due to equalization of forces microscopically, at the macroscopic level no pressure vessel is required to support the process. 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 as judged by RO operations experience [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 and a re-concentrating RO polishing step can complete 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).

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 all the necessary driving force for water recovery in the form of osmotic pressure differential. FO bag treatment for the LWC-WRS is well studied at this time 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 evaluating four different liquid food products as the osmotic agent and seawater as source water in the LWC-WRS application.

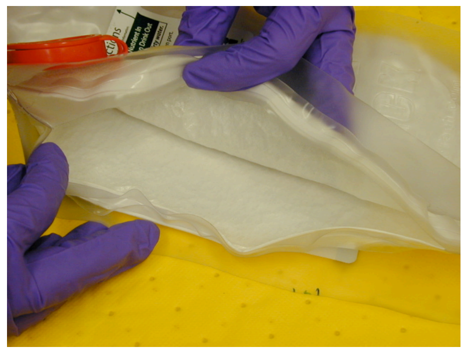


Figure 4 X-Pack ® FO membrane bag opened to show internal cellulose triacetate membrane

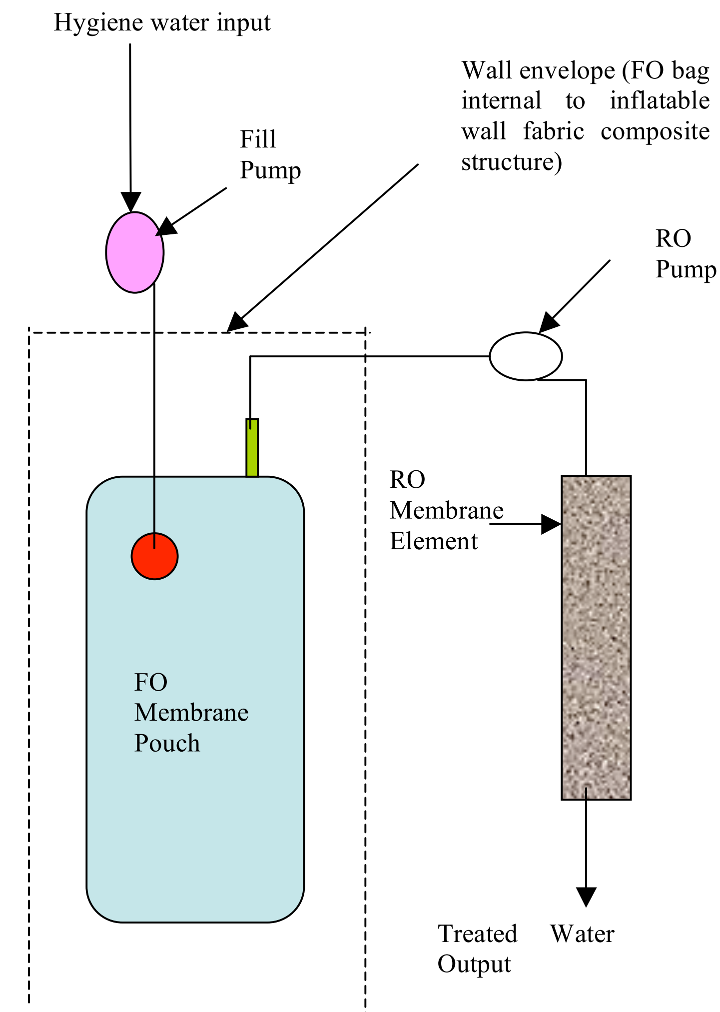


Figure 5 New FO/RO Water Wall System Concept

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 stable 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.

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]. However, both membrane hardware configurations shown for DOC are extremely similar in shape and appearance to pressurized hydraulic applications for membranes and 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.

Because of 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 for the DOC study indicate that primary treatment of hygiene waters is acceptable for a drinking water treatment. FO bag element treatment potential can also be extrapolated from LWC-WRS testing results which 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.

Figure 6 Flat sheet FO membrane element

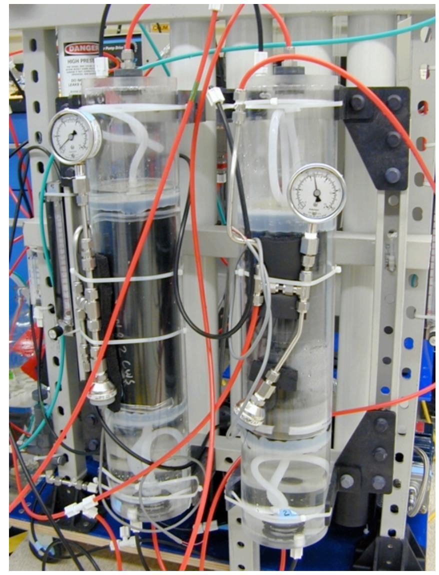


Figure 7 Spiral wound FO membrane elements as mounted in the DOC system

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) 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 a simple and small foot print RO systems. 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.

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

Figure 9 Spiral wound FO membranes

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 by way of http://www.flickr.com/photos/bldgblog/512805504)

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 by way of http://library.thinkquest.org

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

A. 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 wastewater and reject brine are both close enough to a specific gravity of 1.0 so that 1 kg and 1 liter of the material are consider interchangeable units of measures throughout this discussion.

At this rate of use, an active membrane would last 10 to 20 cycles depending on 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 project 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 are given in Appendix A to illustrate the process described above.

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 140 g
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.

III. Solids/Residuals Processing in Membrane Walls

Once the wastewater and brine sequestration role of the embedded membrane bag system is fully exploited, 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 wastewaters. The composition of the 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. Because of 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 here and in the associated detailed calculations in Appendix B and C is a rigorous analysis of the digestion mass balances and products for solids handling for both planetary base and transit mission wastewaters. This discussion is intended to give a credible theoretical basis for considering the membrane water wall as a wastewater residuals 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 discussion 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 chemical process treatment within the same design envelope, though likely with less optimal results for the final solid product.

However, the real function of these sections is to give the space architect the feel for how this material would work, and that we know that it would work based on off the shelf materials and well understood engineering techniques. 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 architectural 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.

A. Composted Biosolids for Hydrocarbon Wall Shielding: the Adobe Brick Wall

For hygiene water rich planetary base wastewaters, 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 re-injected 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 make up 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 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 hydrocarbons 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 scenario based variability an 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 Wash Water	4.09	Urine Solids	0.06
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 is given in Appendix B.

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 solids processing approach, as well as producing fundamentally different final products and launch mass results.

B. 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 wastes other than water treatment residuals from humidity condensate and urine are handled in an entirely separate process. The resulting transit wastewaters are 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 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 wastewaters 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 in Appendix C.

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 with 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 $CaMg(CO_3)_2$, which in natural deposits goes 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 this should be recognized for water weight mass balances, but is presented in the anhydrite form for stoichiometeric 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, still sealed within the bag to be dried in forms probably still never being removed from the FO bag.

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. 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/or making room for a new set of treatment bags.

IV. Air Trace Contaminant Control Concepts in Membrane Walls

Water treatment within the water wall architecture is based on proven technology and methods. Solids processing has not been tested within 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 is much more speculative at this point and is presented here to give an idea of how future concepts in this area may interact with the more developed water treatment and solid waste architecture previously discussed.

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, but a full development of this concept has not been undertaken for ELS air treatment, and an attempt to do so would be beyond the scope of the current FO membrane hardware research effort. However, the technology of gas exchange membranes is also well developed and can be applied in a conceptual way.

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. These membranes will pass CO_2, O_2, and H_2O in the gas phase, but will not allow liquid water to pass.

V. Advantages of Active and Evolving Membrane Walls

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. Most specifically, it does this through 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 [21] 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 to this point in time. Water or hydrocarbons are superior to metal in that they tend to absorb cosmic ray radiation, which are 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. But 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 could be developed without any 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 vs. return value perspective. In this role human habitation becomes a resource producer rather than a sunk 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 space craft. 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 solids processing discussion earlier.

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 in 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 residuals 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.

VI. 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.

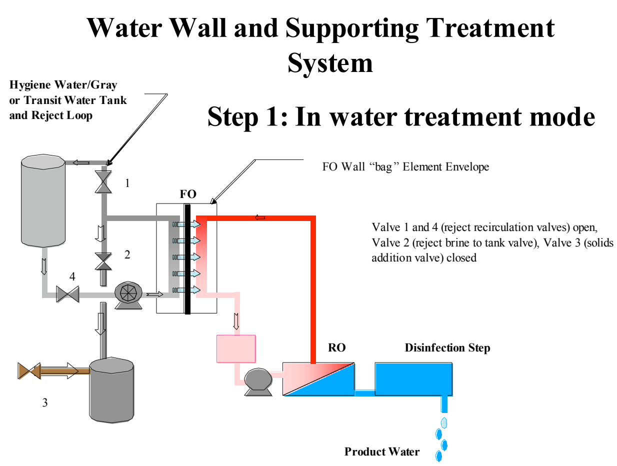
Both current mechanical and/or physical chemical unit process based systems, as well as first generation vascular plant based Closed Ecological Life Support (CELSS), are severely limited because they are not reorganized at the substrate level and are not able to evolve into completely new and unexpected 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.

VII. Conclusion

The membrane water wall is shown to be a viable concept for integrating waste processing into inflatable structures while also providing valuable material resource recovery and radiation shielding functions for the space architect. The water wall is based on well established engineering principles and off the shelf hardware. These membranes and the processes they perform are the result of a long history of NASA life support research that is well documented. Including water treatment within the walls of inflatable habitats will provide unique advantages and can be included in system and architecture planning based on the results of this study.

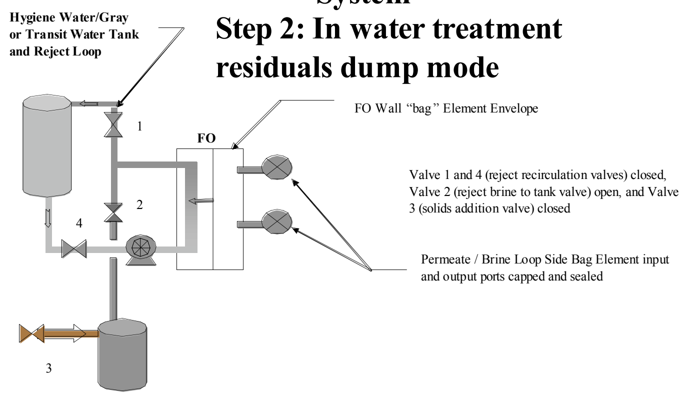
Appendix

Appendix A: Step by step flow schematics for water wall treatment process



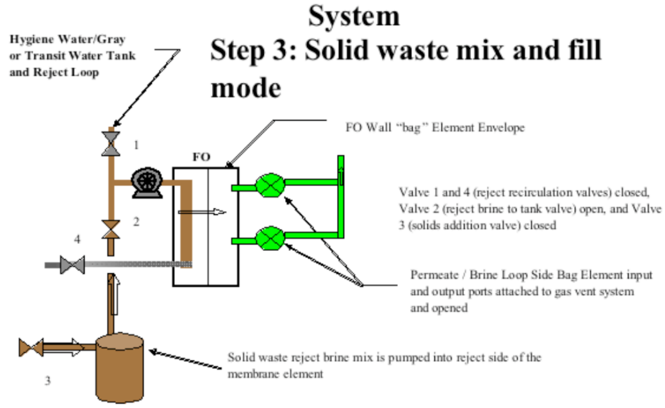
Water Wall and Supporting Treatment System

Step 2: In water treatment residuals dump mode



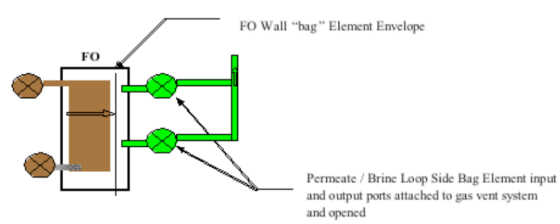
Water Wall and Supporting Treatment System

Step 3: Solid waste mix and fill mode



Water Wall and Supporting Treatment System

Step 4: Solid waste digestion mode



Appendix B: Detailed Calculation for Composting Biosolids

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, will consume a small amount of water, and convert it variously into H_2, HCO_3^-, CO_2, and intermediate organic products such as acetate. It will likely do all of the above in some relative proportion based on waste stream composition [12]. However, 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]:

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

But 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 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, 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.

Appendix C: Nitrogen Conversion Dominated Digestion Stoichiometry and Mass Balance

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

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