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Water Walls Life Support Architecture: System Overview

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This overview describes the several systems that comprise the Water Walls approach to creating a Life Support system using a simple membrane technology to replace the complex and too failure-prone existing life support systems. The primary innovation is to try to achieve reliability through the massive redundancy of inexpensive, passive forward osmosis membrane placed within simple but sturdy polyethylene bags. This overview starts with a chronology of the initial Functional Flow concept and how it was revised and simplified. Then it explains the Process Block approach and how it was ultimately consolidated to achieve more clarity and simplicity at the higher system level while developing refinement and component characterizations at the lower, subsystem level. This work was supported particularly by NASA contract NNA13AA38C funded by the NASA Innovative and Advanced Concepts program, and by the Ames Center Director's Innovation Fund.

Nomenclature

Ammoniafication = The enzymatic process of organic-N conversion to NH4+. It is the method for breaking up urea into usable compounds, including ammonium and nitrates.
Blackwater = Wastewater with fecal solids in it.
$CaCO_3$ = Calcium Carbonate, a by-product of WW thermal and humidity control
$CaSO_4$ = Calcium Sulfate, gypsum, or "astronaut bone precipitate."
CH_4 = Methane gas, significant in life support systems as a byproduct of the *Sabatier Process* to crack CO_2: sequestering the C and liberating the O_2.
Cyanobacteria = Also known as blue-green algae, cyanobacteria generate a high rate of oxygen production with a corresponding rate of CO2 uptake.
Denitrification = The dissimilatory reduction of Nitrate (NO_3-) to nitrous oxide (N_20) or dinotrogen (N_2). It occurs among a diverse array of microbes. Denitrification is strictly anaerobic and will convert nitrate nitrogen to N_2 gas.
ECLSS = Environmental Control and Life Support System; implies a conventional electro-mechanical system.
Flux Rate (urine) = The flux rate is the rate at which water or another fluid crosses the membrane and is equal to the production rate of the urine/water processing FO bag.
FO = Forward Osmosis is a natural process in which the osmotic potential between two fluids of differing solute/solvent concentrations equalizes by the movement of solvent from the less

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concentrated solution to the more concentrated solution. Typically, this exchange occurs through a semi-permeable membrane that separates the two solutions, allowing the solvent to pass through the membrane pores but not the solute. This solvent flux continues until the osmotic potential across the membrane and solute/solvent concentrations equalizes.

Graywater = Hygiene water, laundry water, dishwashing water, or other water flux with surfactants in it.

ISS = International Space Station

Latent Heat = 1. The heat required to convert a solid into a liquid or vapor, or a liquid into a vapor, without change of temperature. 2. The heat absorbed or radiated during a change of phase at constant temperature and pressure. 3. The heat absorbed by air when water vapor condenses.

MCWL = Maximally Closed Water Loop Wastewater processing loop that can achieve the highest degree of closure because it includes graywater recovery with urine, condensate, and blackwater/solids processing.

NH_3 = Ammonia; significant as a transitional stage of nitrogen compounds from urine and urea to nitrite and nitrate

NH_4 = Ammonium, also shown as the ions *NH_4— and NH_4+*

NIAC = NASA Innovative and Advanced Concepts program

Nitrification = Nitrogen fixation in Water Walls occurs biologically; it refers to the ability of an organism to transform N_2 from an atmospheric gas into NH_3. The NH_3 is eventually attached to organic compounds and incorporated into algae or other plants. Nitrification is aerobic and will eventually convert all urea and ammonia nitrogen into nitrite and then to nitrate

Nitrogen Cycle = The progressive transformation of nitrogen compounds from urea to ammonium brine to nitrite to nitrate.

OA = Osmotic agent, typically salt, brine, or sugar.

OMD = Osmotic Membrane Dehumidifier

PCO = Photocatalytic Oxidation

PCWL = Partially Closed Water Loop Wastewater processing loop that cannot achieve the highest degree of closure because it does not include graywater recovery with urine, condensate, and blackwater/solids processing.

PEM = Proton Exchange Medium or Proton Exchange Membrane

Sensible Heat = 1. The amount of energy released or absorbed by a chemical substance during a change of temperature. 2. Heat that changes the temperature of a material without a change in state, such as that which would lead to increased moisture content.

SMAC = Spacecraft Maximum Allowable Concentration, a set of NASA standards to define the maximum level of contaminants acceptable within the crew cabin atmosphere.

SVOC = Semivolatile Organic Compound

TiO_2 = Titanium dioxide; exposure to ultraviolet light triggers a biostatic effect that kills microbes of many varieties on the coated surface

TOC = Total Organic Carbon

VOC = Volatile Organic Compound; all organic carbon that is not part of colloidal or gross particulate matter.

WW = Water Walls Life Support Architecture

I. Introduction

IN 2012, the National Research Council (NRC) of the National Academy of Sciences published its comprehensive review of NASA technology programs, with particular attention to long duration human mission. The NRC concluded (p. 184):

> *ECLSS for missions beyond Earth orbit (for spacesuits, spacecraft, and surface habitats) are critical for safety and mission success. It was a loss of an oxygen tank and subsequently a compromise of a portion of the ECLSS loop (CO_2 removal) that nearly cost the Apollo 13 crew their lives. In missions without early return capability or remote safety depots,* ***the ECLSS system must be as close to 100 percent reliable as possible and/or easily repairable with little or no resupply.*** *Because air and liquid systems are sensitive to gravity level, extended testing of systems in reduced gravity may be necessary before they are integrated into exploration spacecraft.* ***Current ISS experience with both U.S. and Russian ECLSS systems shows significant failure***

rates that would be unacceptable for an extended human exploration mission. *In many cases, ISS ECLSS equipment has been launched and implemented without microgravity testing.* ***[Emphasis added]***

The WW team was already on the case. The challenge of long duration, passive, and regenerative life support generated the reason the WW Architecture team formed originally in 2011. The WW concept addresses exactly this set of concerns that the NRC identified. Even before the WW Architecture team coalesced, its members anticipated the latter warning about flying ECLSS without microG testing, the team flew a urine processing experiment using FO bags on the last Space Shuttle Flight, 8 July 2011 (Flynn, *et al*; 2012). However, the WW Life Support Architecture takes a profoundly different approach than the conventional electromechanical systems. Instead, WW emphasizes passive processes through the use of forward osmosis membranes that attempt to replicate the much more reliable and robust processes in nature.

The ***Long-Term goal*** is to design, engineer, build, test, and operate a passive FO life support system that does not involve high duty-cycle, high wear electro-mechanical systems but instead uses pumps and valves only intermittently to move fluids. This system can provide highly reliable, massively redundant life support for long duration (e.g. more than a year) life support systems for missions to asteroids, Mars, or beyond. The integrated, yet modular Water Walls Life Support System allows for a comprehensive and flexible system, with near-unlimited redundancy, so critical to long-duration missions. The membrane-based technology, combined with other mainly passive systems, provides maximum sustainability of the habitat and crew using the minimal amount of natural resources. As the Water Walls System develops, it will enable a sustainable human presence beyond Earth.

The ***Short-Term goal*** is to devise a functional and physical architecture for water walls that provides an integrated framework for the chemical, electrical, mechanical, plumbing, and structural subsystems that will support the passive water walls ecosystem. Achieving this goal will help generate the parameters for sizing the subsystems, most particularly each of the five FO life support capabilities plus the radiation shielding. What the Short Term goal does NOT include is chemistry and biology advances that should be properly supported by baseline Life Science and Life Support funding. The ***Short-Term goal*** bounds the Phase-1 (and hopefully the Phase-2) research areas to distinguish those that the project could cover in Phase 1.

FIGURE 1. Hydration Technologies Inc. Seapack® Desalination Bag. Water Walls uses this general type of bag for urine processing experiments, to prepare fecal simulant, and for other osmotic processes. Photo: Marc M. Cohen.

The Water Wall Life Support Architecture concept presents an alternative approach to designing, building, operating, and replacing life support systems for long duration spacecraft. When fully developed, Water Walls (WW) will provide the complete suite of functions as the current electromechanical environmental control life support systems (ECLSS), but will do so with higher reliability, redundancy, and the additional benefit of providing radiation shielding. WW accomplishes this goal by applying passive membranes that replicate the way living organisms contribute to maintaining the biosphere on Earth. The membrane technology with the widest application in WW is *forward osmosis*. Forward osmosis (FO) is a natural process that moves fluids through a membrane as required to enable biological processes. Because it is passive, it involves less complexity, fewer parts, and less risk from mechanical failure than conventional electromechanical environmental control and life support system (ECLSS) hardware.

The key that makes WW possible is the FO *bag* -- an inexpensive polyethylene envelope with one or more FO membranes in it, as shown in FIGURE 1. The thrust of the WW project is to develop more FO bag types, and other specialized membrane bags that can perform additional life support functions, particularly CO_2 removal and O_2 production, waste treatment for urine, wash water (graywater), and solid waste (blackwater), climate control, and contaminant control. Making WW far more reliable than mechanical ECLSS becomes feasible because the FO bags are so inexpensive, it is feasible to use them up – to consume them – in a controlled manner, without any single point of failure. When one unit or module assembly uses up its capacity, the control system turns it off and switches on the next unit in sequence to maintain the processes. The used bags can then be cleaned, refilled and reused, or relocated to where their mass can add radiation shielding. The crew need not worry about critical systems failing suddenly because the bags will be failing in a planned, predictable, and replaceable manner from an ample supply of cheap bags throughout the mission.

II. The Functional Flow Concept

In 2012, the Water Walls team (Michael Flynn, Principal Investigator, NASA-Ames Research Center) won a NIAC Phase 1 grant of $100k to develop the Water Walls concept for a human spacecraft living environment.[5] In addition to the Phase I grant from NIAC, the WW project attracted additional support. Shortly after NIAC announced the award to the WW team, the Ames Center Director, Pete Worden provided $100k in matching funds that enabled the addition of two co-investigators: Rocco L. Mancinelli, PhD for air revitalization and Sherwin Gormly, PhD for waste processing.

A. Module Assembly

An initial goal leading up to Phase I was to design a physical WW module assembly for the WW system to provides life support, dietary supplement, and radiation shielding capabilities. This module assembly appears in FIGURE 2. The significance was that creating this assembly design would enable all the subsystem and component development to follow in later phases and under separate funding lines. The innovation was that connecting all the FO processes together in the same functional flow matrix is a new approach that translates the natural environment on Earth into a bio- and physical-chemical biomimetic system. The approach was CAD modeling using Vectorworks Designer.

This module assembly led the team to understand the characteristics of each type of FO bag, and what they would require for connection to a larger assembly. However, that module assembly idea proved too simplistic and naïve insofar as it presupposed a fixed, optimal ratio of the several types of FO bags. Also, the representation of the octagonal bags surrounding rectangular organic fuel cells proved premature to be so geometrically specific, so in later representations, the team used the simple "double square" rectangles for the most generic FO bag geometry.

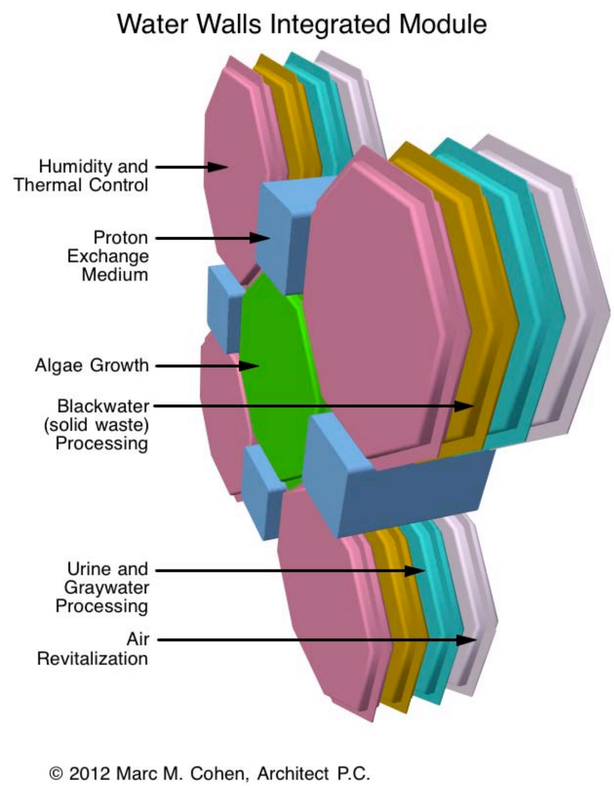


FIGURE 2. Water Walls Multi-Cell Module. Credit: Marc M. Cohen.

On 26 Feb 2013, Taber MacCallum, CEO of Paragon Space Development Corporation, stated to New Scientist that the Inspiration Mars Flyby mission would use the Water Walls system for life support and radiation shielding (Aron, Grossman; 2013, March 1). The WW team was already pursuing an effort to conduct radiation beam testing of some WW materials; they added fecal simulant (Wignarajah et al, 2006; Nabity et al, 2008) to the test plans. The

[5] NASA Ames Contract NNA13AA38C for the 2012 NIAC grant: Water Walls Architecture: Massively Redundant and Highly Reliable Life Support for Long Duration Exploration Missions.

Bioengineering Branch at Ames Research Center approved funding to support this radiation shielding beam testing. The WW team describes that effort in the companion 2014 ICES-26 paper "Water Walls Radiation Shielding: Preliminary Beam Testing of Ersatz Solid Waste Simulant," which is incorporated into this final report as the Radiation chapter. The Bioengineering Branch at Ames also won a NASA Game-Changing Technology grant supporting a new initiative to develop a new generation of microbial fuel cells, for which Michael Flynn is the Co-Investigator. This parallel funding stream helped the WW team to conceptualize the organic fuel cell at the center of FIGURE 3.

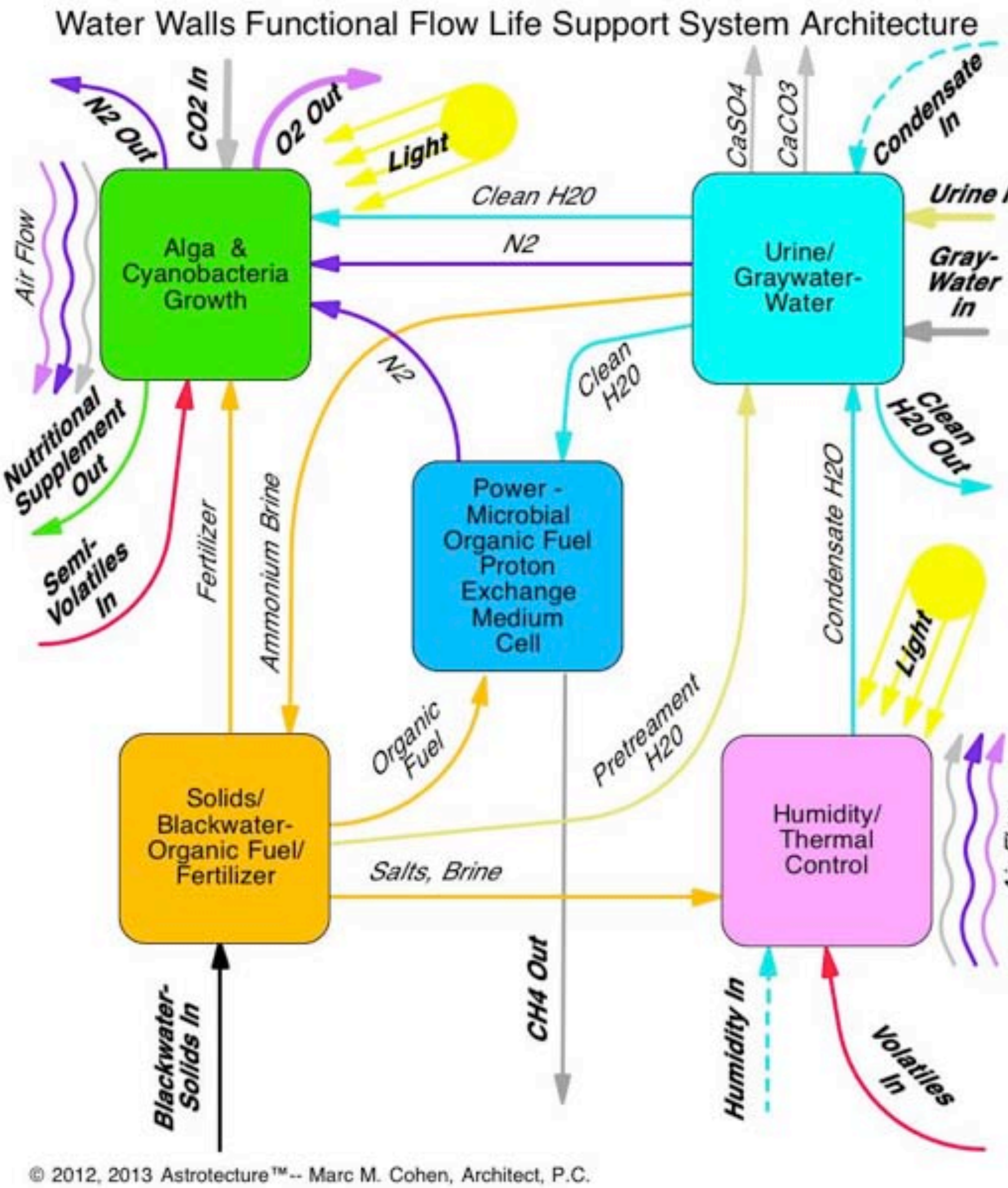


FIGURE 3. WW Functional Flow System Diagram. Credit: Marc M. Cohen.

B. Functional Flow Architecture

The next step was to design the functional flow pattern that would provide the operational matrix for the WW module assembly was to design the functional relationships and process flows among the FO bags and PEM cells. The significance was that the FIGURE 3 *Functional Flow Diagram* sits at the heart of the system architecture (Cohen, Flynn, Matossian; 2012).

It shows how to create the "life support economy" in a space habitat. The functional flow diagram explains the regenerative and closed-loop aspects of the WW. It shows how the effluent from one FO bag is the feed for another bag or organic fuel cell and where the output consumables derive. The approach was for the functional flow diagram to explicate how the WW works by:

1. Specifying the seed stock (e.g. salts, nitrates, water),
2. Identifying the bags that require airflow and light,
3. Describing the waste products from the space cabin environment that the WW system processes,
4. Assigning the process flow outputs within the WW system,
5. Explaining how the WW system provides its own power for valves, pumps, and sensors through the Proton Exchange Medium Organic Fuel Cell(s), and
6. Defining the consumable outputs: potable water, O_2, N_2, and nutritional supplement.

As a way of analyzing and "bookkeeping" the functions that would occur within each WW FO bag or unit, the team developed a matrix to identify and track those processes. TABLE 1 presents a simplified version of this matrix. The purpose of this bookkeeping was to establish a method of sizing the subsystems – how many bags or units of each type would prove necessary for the functional flow concept to balance and operate. The sizing plan recognized that different mission types, durations, and crews might need different life support "economies," in which the ratios of the FO bags could vary to meet the needs of the "economy." The approach began from a "minimum functionality" paradigm of the basic numbers to enable the WW system to perform all its process functions, geared to supply one algae growth bag with nitrate fertilizer from the graywater-urine/water FO bags and blackwater/solids FO bags.

TABLE 1. Matrix of Water Walls Subsystems and the Processes they Perform.

WW Primary Function (Inputs and Outputs)	Humidity Control	Algae Growth	Blackwater/ Solids	Organic Fuel Cell	Urine/ H2O
O2 Revitalization		X			
CO2 Removal		X			
Denitrification/ Liberation of N_2			X	X	X
Uptake of Nitrogen & Salts	X	X			
Clean Water Production	X				X
Urine/Graywater Processing					X
Humidity Control	X				
Nutritional Supplement		X			
Blackwater Processing			X	X	
Electrical Power Production				X	

NITROGEN CAVEAT: A common misconception about the nitrogen economy is that it interacts with the mass balance issues. However, in a nutshell, nitrogen is not a mass balance problem at all. Instead it may arise as a trace contaminant problem in the form of ammonia that causes a mass balance problem in physical chemical processes because it is difficult to remove it from water. Instead, give algae this same ammonia nitrogen and it's gone. Ergo, it's not a mass balance problem in biological systems. According to one set of WW calculations, the amount of nitrogen variability in question is about 0.5 kg of nitrogen per crewmember year.

One of the paradoxes of life support processing is the biological nitrogen problem. Urine is high in ammonia nitrogen in the form of urea. It is so high in urea that it causes a problem in biological treatment. Alternately treated water is low in biologically available nitrogen, and thus this is potentially limiting for the air regeneration, fuel cell, and food production algae elements to be discussed later. In the emergency FO urine system, as well as any system used to produce water using only membrane and adsorbent processes, greater nitrogen rejection is highly desirable. However, selective "leaking" of biologically available nitrogen to the treated water stream prior to solids composting may actually be beneficial once the algae based air regeneration bag elements are added to the system. Further development of this dynamic concept for both its mass balance and membrane section implications will belong in the Phase II concept development.

The initial approach of postulating an ideal, fixed ratio among the FO bags proved unsuccessful. It was overridden by the way that all the nitrogen compounds play a cardinal role in determining mass balance and mass-balance flows. These nitrification and denitrification processes prove the most crosscutting. TABLE 1 records the structure of the mass inputs and outputs from the various bags or cells. The boxes bounded by the triple border show the key intersections of the WW subsystems and the "nitrogen economy" processes. Managing the nitrogen compounds such as urea, ammonium, and nitrates that dominate the nitrogen cycles or economy emerges as critical to controlling the mass balance within the WW system.

III. Hierarchy of System Integration

Developing the TABLE 1 matrix with its focus upon the processes within the WW subsystems led to an examination of the processes themselves. It portrays the WW system schematically as a pyramid made up of horizontal layers. FIGURE 4. illustrates this pyramid, which expresses the system-integration challenge. Not only must WW integrate varying technologies and subsystem within each layer, but also each layer must integrate vertically within the WW hierarchy. The Functional Flow Concept sits at the peak of the pyramid. Beneath it lies the Process Blocks that embody the major constituent systems. The subsystems make up each process block; the component level bags, tubing, valves, pumps and sensors make up the subsystems.

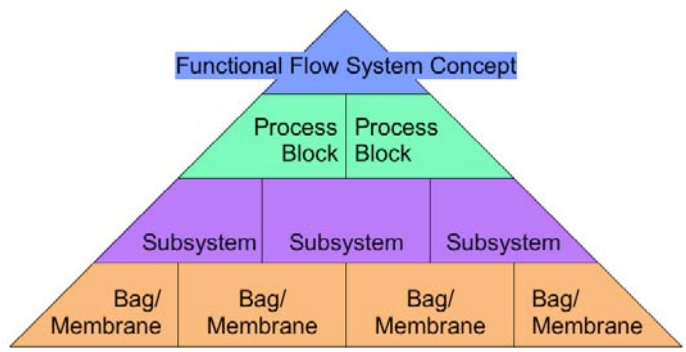


FIGURE 4. Water Walls System Integration Pyramid.

IV. The Process Block Concept

This emphasis led to the second major concept of the WW System: the Process Blocks that lies beneath the Functional Flow Level. These Process Blocks constitute units of integration for Climate Control, Air Revitalization, and Energy & Waste. The flows among these Blocks are more specific than the System Functional Flow. The Process Block Diagram shows how the three blocks, along with their component subsystems, interact, and it recognizes the human Crew as a key component within the overall system. The diagram highlights the specific input and output flows between the Blocks, and also indicates necessary environmental conditions per Block such as light and airflow.

FIGURE 5. presents the Process Block level of the Water Walls Architecture. At this level, the WW Architecture consisted initially of four process blocks:

Block 1. Climate Control,
Block 2. Contaminant Control,
Block 3. Air Revitalization, and
Block 4. Power and Waste

These Process Blocks are each comprised of several subsystems that will be described in the following level. What is important about the combining of these subsystems and their processes into blocks is that they allow the consolidation of many of their common inputs and outputs. FIGURE 5 shows the initial Process Block Diagram configuration with the four Blocks and the mass flow connections among them.

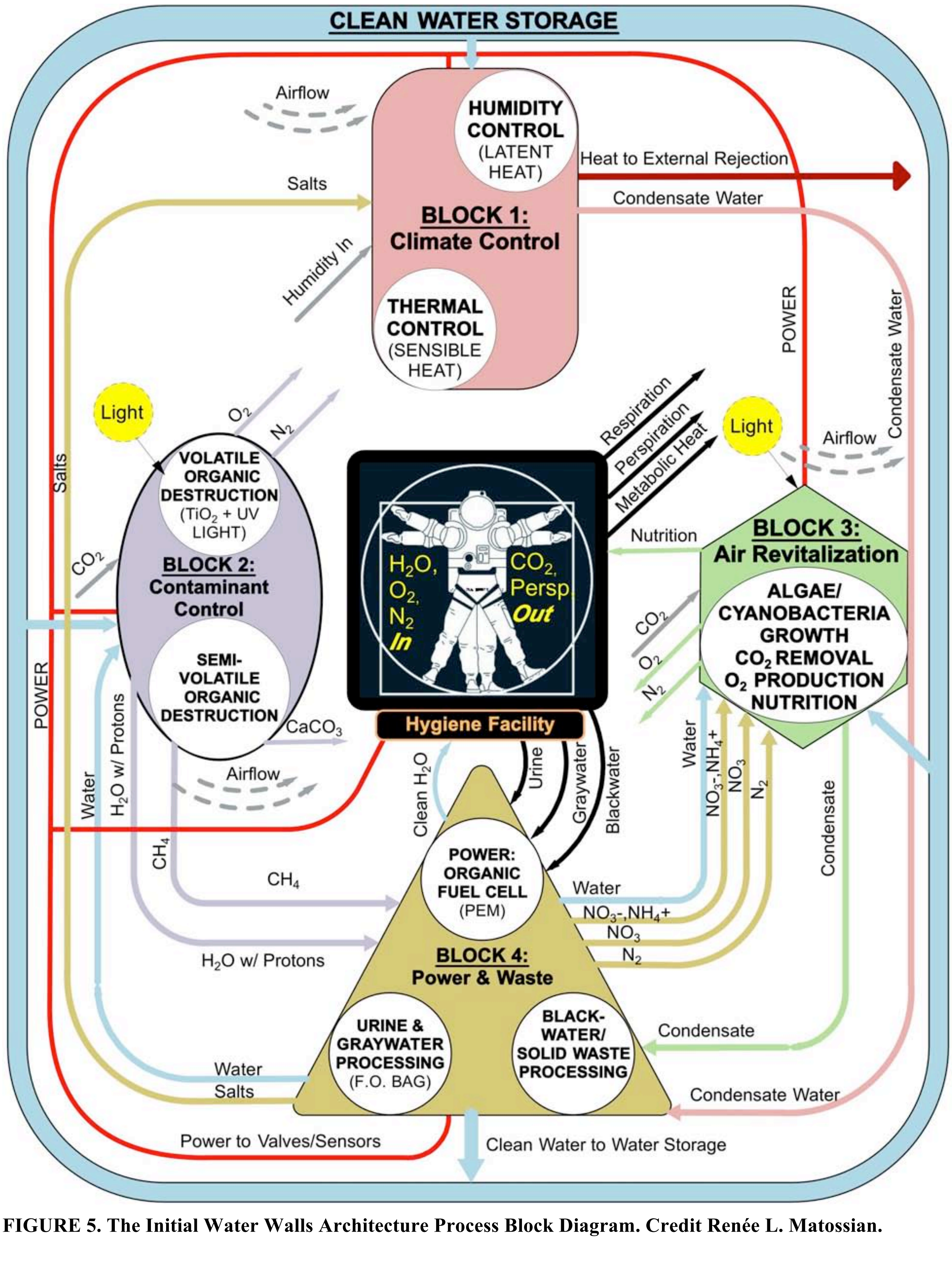
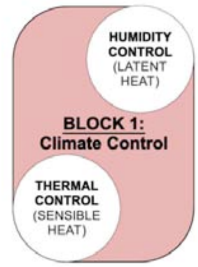


FIGURE 5. The Initial Water Walls Architecture Process Block Diagram. Credit Renée L. Matossian.

A. The Climate Control Block 1

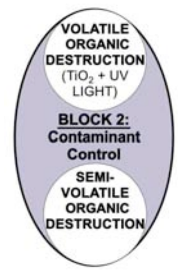
The Climate Control Block combines two subsystems, Thermal Control and Humidity Control. Both these subsystems receive their inputs from vigorous air circulation over the external FO membrane. Both subsystems consume salts and brine; both produce condensate that flows to **Block 4**. Thermal Control handles the sensible heat associated with the dry air temperature. Humidity Control handles the latent heat that the humidity in the air carries. Both subsystems must reject the heat to the exterior of the spacecraft.



An important precedent for the Humidity Control subsystem resides in the Ames/JPL Air Team's development of an air dehumidification system that relies on the Nafion membrane. Although the purpose of the air group's system differs from Water Walls insofar as its purpose is to achieve superior drying of the air before passing it into a Sabatier reactor to crack the CO2, the use of the passive membrane technology is instructive.

B. The Contaminant Control Block 2

The three main contaminants are particulates, semi-volatile organics carbon compounds (SVOC), and volatile organic carbon compounds (VOC). Since the handling of particulates is well advanced using HEPA filters and in some cases, electrostatic devices, it does not figure in the development of Water Walls at this time. SVOCs and VOCs persist as a challenge in current spacecraft. Controlling both SVOCs and VOCs by destroying them arises to a top-level health and safety requirement to maintain a cabin atmosphere that conforms to NASA's Spacecraft Maximum Allowable Concentration (SMAC) level standards. Like **Process Block 1**, the Contaminant Control **Block 2** obtains its material primarily through airflow. The subsystem design for contaminant control asserts "primarily from the atmosphere," because many of these contaminants show up in condensate from Block 1; one of the most common ways of monitoring SVOCs and VOCs is to measuring them in condensate output from the thermal control system.



However, at this time, the Water Walls project focuses on the SVOCs and VOCs extracted directly from the cabin air. The primary means of breaking down VOCs is to expose them to light while in contact with a catalyst such as TiO_2. Ultraviolet light can be much more effective, but ambient cabin lighting also works, albeit not as quickly. SVOC destruction will occur in the FO bags that process water and have an exchange with the cabin atmosphere. That set of conditions means primarily the algae bags in **Process Block 3**.

Among the principal inputs to **Block 2** are CO_2 and CH_4 (methane). More complex VOCs will require further analysis for these methods of destruction. The outputs include O_2, N_2, and $CaCO_3$, calcium carbonate.

The distinction between SVOCs and VOCs is important for the physical/chemical process electromechanical life support systems. However this distinction is but is wholly absent from biological process engineering in wastewater. This distinction can generate a language barrier between atmospheric life support researchers and traditional ECLSS engineers. So for clarity, VOC refers to all organic carbon that is not part of colloidal or gross particulate matter.

C. Air Revitalization Process Block 3

Unlike the other three Process Blocks that show multiple subsystems, Air Revitalization incorporates just one, the Algae and Cyanobacteria Growth Subsystem. This unitary subsystem performs the greatest range of services of any of the Process Blocks. It removes CO_2 from the cabin atmosphere and sequesters the carbon in the tissue of the algae and cyanobacteria where it can do no harm, instead becoming part of the food chain, courtesy of photosynthesis. The algae sequester the organic carbon from the CO_2, and as part of the photosynthesis equation, the algae release O_2 from H_2O, which returns to the cabin atmosphere, while the O_2 from the CO2 becomes part of a glucose molecule

$$6CO_2 + 6H_2O \text{ ------> } C_6H_{12}O_6 + 6O_2 \qquad \text{Photosynthesis equation.}$$

In addition, the algae and cyanobacteria can produce foodstuffs, diplomatically called "nutritional supplement," Block 3 intrinsically performs SVOC destruction. The investigation of SVOC destruction must focus on the mixture of algae and heterobacteria species best suited to this task. In all these respects the "Four-in-One" **Block 3** behaves as if consisting of four subsystems while working as a unitary process.

One leading challenge for long duration missions is to process this carbohydrate and protein to supply a feedstock to prepare food that is healthy, nutritious, and above all, acceptable to the crew, who may need to eat it for months or years. For photosynthesis the unique input is the light itself. Referring to FIGURE 5, the essential inputs for **Process Block 3** include N_2, CO_2, H_2O, and light. An additional input may be fertilizer from **Process Block 4** to **Block 3** in the form of NO_3—, NH_4+, and NO_3. With respect to the breakdown products of SVOCs, the working assumption is that they will prove *de minimus* in terms of the fundamental process cycles, although it will be necessary to monitor for any toxic effects from the breakdown of those contaminants. Outputs from **Block 3** include O_2, N_2, and H_2O.

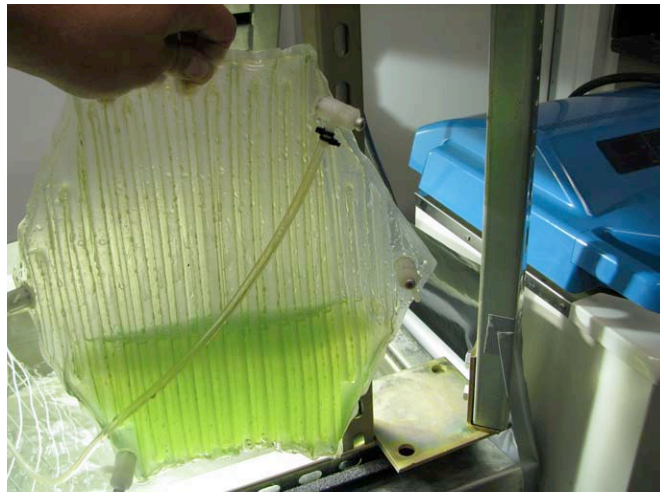
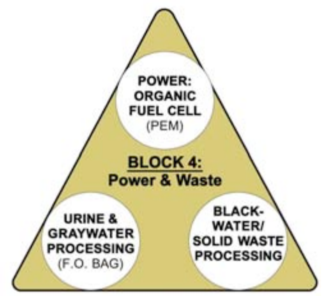


FIGURE 6. Experimental Green Algae Growth FO Bag, approximately 3.5 cm thick. NASA photo.

D. Power and Waste Process Block 4

The Power and Waste Process Block 4 combines three subsystems:

1. The Microbial Fuel Cell, (MFC) is also known as the Bioelectrochemical System (BES), each one incorporating a Proton Exchange Medium (PEM) and typically at least two FO membranes,
2. The Urine and Graywater Processing Subsystem, generally an FO bag, and
3. The Blackwater and Solid Waste Processing Subsystem, generally takes the form of an FO bag, although there are alternatives in the form of equally passive FO membranes stretched across sealed, pressurizable frames or spiral-wound in pressurizable, cylindrical tubes.



The subsystems within **Process Block 4** are the most tightly bound together in terms of the functional flows among them. Most tellingly, the Blackwater and Solid Waste unit produces partially treated waste that flows to the Microbial Fuel Cell to be consumed as fuel. In a similar way, the Urine and Graywater processing subsystem passes ammonium brine (NH_4Cl) to the Blackwater and Solids unit. The Urine Graywater bag also provides clean H_2O to the Microbial Fuel Cell and the Blackwater Solids unit sends "pretreatment" water (actually secondary or tertiary treated) to the Urine Graywater bag. These **Block 4** subsystems will develop as the most complex biologically, electrically, and chemically. The inputs to **Block 4** include condensate, urine, graywater, and blackwater/solids. The outputs include clean drinking water, N_2, gypsum ($CaSO_4$), calcium carbonate ($CaCO_3$), nitrate fertilizer, and methane (CH_4).

E. Revised Process Blocks

After a year of study, the WW team found insights into the deep structure of the Water Walls Architecture. These insights led the team to modify the original FIGURE 5 Process Block Diagram substantially. These changes reallocated some subsystems among the process blocks, modified the mass flows and subsystem system connections, and reduced the blocks from four to three. This revision eliminates the original Contaminant Control Process Block 2 by transferring SVOC destruction to the Air Revitalization Block where SVOC destruction occurs regardless of where the diagram shows a bubble for it. The revision transfers the VOC destruction to the **Climate Control Process Block 1** because of the need for substantial and continuous airflow for both sets of processes that ideally can be collocated together. These alterations led to a renumbering of the process blocks themselves. In the original FIGURE 5 schematic, the numbering ran from left to right in three rows. In the revised FIGURE 7, the blocks are renumbered in clockwise fashion from 12:00 for **Block 1** to 3:00 for **Block 2** to 6:00 for **Block 3** and to 9:00 for a new block placeholder. This new Process Block 4 will be reserved for higher order plants in a future iteration of the Water Walls System. It stands as a "plug-in" for a future greenhouse to cultivate plants.

At the center of FIGURES 5 and 7 stands a space-suited "Vitruvian Man," representing an icon of the human being. The human Crew system requires O_2, potable water, and food as bare-minimum inputs for survival, and releases CO_2, perspiration, waste, respired water vapor, and metabolic heat to be accommodated by the surrounding habitat and hygiene systems. The WW Process Blocks and their subsystems support and balance these requirements within the closed system on the spacecraft or in the space habitat.

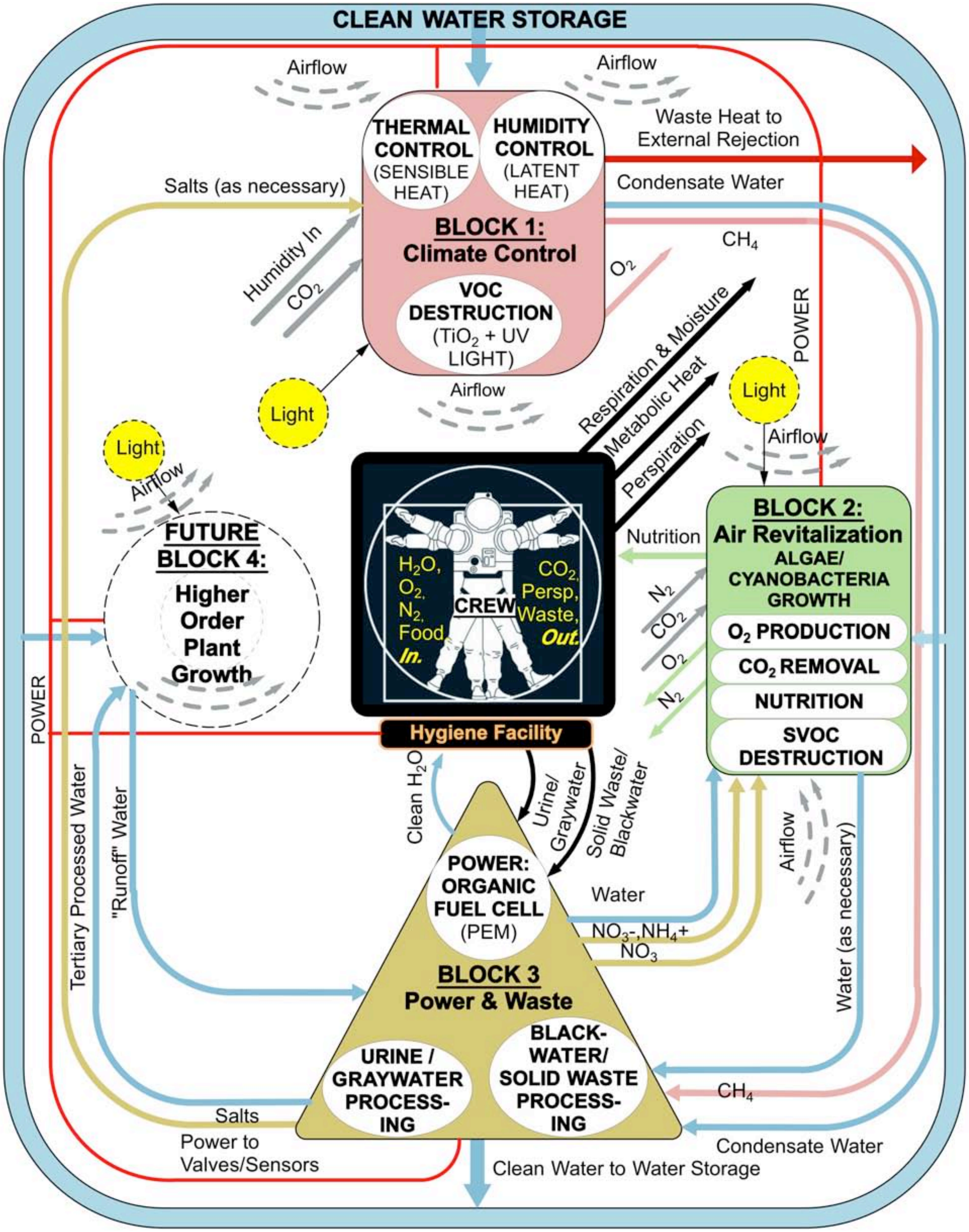


FIGURE 7. Revised Process Block Diagram that shows the transfer of SVOC destruction to the Air Revitalization Block 2 and VOC destruction to Climate Control Block 1. It also shows the placeholder in Block 4 for future higher order plants for food crops. Credit: Renée L. Matossian, Marc M. Cohen.

In the new Process Blocks FIGURE 7, **Block 1,** Climate Control, is composed of 3 subsystems: Thermal Control (in the form of temperature-sink WW Bags), Humidity Control (utilizing brine-filled WW Bags), and VOC Destruction (consisting of TiO_2-duped substrate exposed to light). **Block 1** requires the input of airflow, light, humidity, salts, CO_2 and H_2O, and it expels waste heat, condensate water, O_2, and CH_4.

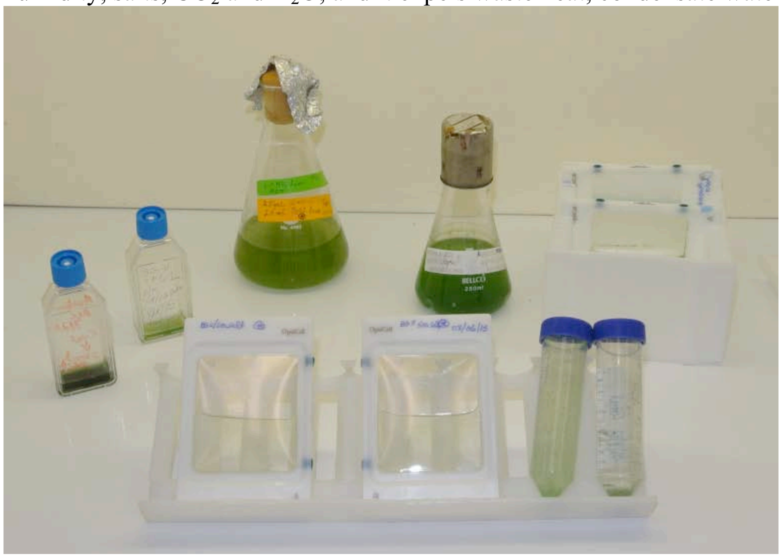


FIGURE 8. Cyanobacteria Baseline Control Experiment for Cyanobacteria in Rocco Mancinelli's (BAERI) Lab at NASA Ames Research Center (Building N239A, Room 201).

Block 2, Air Revitalization, is responsible for CO_2 absorption and O_2 production (courtesy of WW Bags populated with photosynthetic algae and/or cyanobacteria), and also SVOC Destruction (via WW bags containing algae and heterobacteria). These subsystems predominately require the input of light, airflow, CO_2 and H_2O, while releasing O_2 into the cabin. Algae and edible Spirulina can also be harvested from this Block to provide a nutritional supplement for the Crew on long-duration missions.

Block 3, Power and Waste, serves to process the urine/graywater and solid waste/blackwater from the Crew and cabin (using WW processing bags) while resupplying the Climate Control Block with re-constituted salts and salt brine, and providing reclaimed water to be reconditioned, polished, and redistributed back to the habitat systems. **Blocks 3's** organic fuel cells will also produce minimal power to run the basic valves, fans, and sensors imbedded in the WW system.

Future Process Block 4 represents a potential "plug-in" to accommodate higher order plants to grow food and to create a more Earth-like and "natural" environment in the space habitat or spacecraft. With respect to the prospective Block 4, Plant Growth, the WW team acknowledges an engineering bias against including higher order plants within a life support system. The reason for this opposition is the received wisdom that it will never be economical in terms of equivalent system mass to fly crop plants or grow them in a surface habitat compared to a logistics system that carries or delivers them freeze dried to the crew. However, any serious consideration of a permanent lunar or Mars base must take into account the extremely long duration of such a mission that varies inversely with the reliability of resupply. For this reason, a future iteration of Water Walls will take a serious look at how to integrate food crop plants more complex, nutritious, tasty, and varied than algae.

V. Subsystem Concepts

The subsystems make up the Process Blocks. This section describes the key features of the subsystems and provides examples of three in detail: Humidity Control (latent heat) in **Block 1**, the Algae Cycle and the installation of the algae bags in **Block 2,** and the Wastewater Cycle in **Block 3** of TABLE 5. FIGURE 9 shows the subsystem level in the WW Integration Pyramid. TABLE 5 summarizes the subsystems within each Process Block. Some "new" subsystems such as contaminant control emerged as major topics during the course of the Phase 1 project, but were outside the scope of the effort and of the available funding to go into much detail.

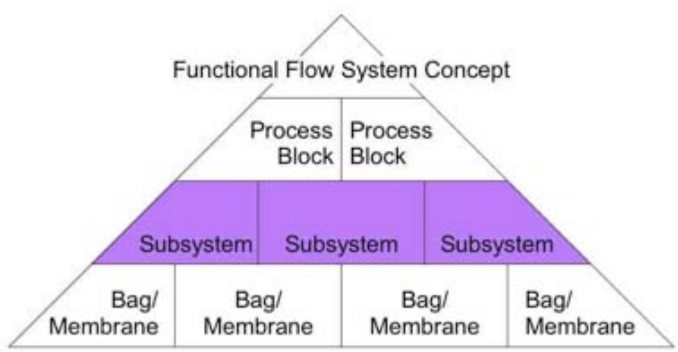


FIGURE 9. Subsystem Level in the Water Walls System Integration Pyramid

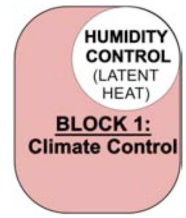
F. Process Block 1 Climate Control

Climate Control in a spacecraft consists largely of controlling three parameters: humidity, pressure, and temperature. The Water Walls system does not control the pressure, which is managed by mechanical-pneumatic systems. However, WW does control humidity and temperature. There is a nexus between humidity and temperature that encompasses two kinds of heat: latent heat that the moisture in the air carries – the humidity, and sensible heat that the air molecules carry. The Climate Control Block provides a separate subsystem to handle each form of heat.

TABLE 5. Water Walls Process Blocks and their Subsystems

Process Block 1: **Climate Control** Humidity Control (Latent Heat) Thermal Control (Sensible Heat) VOC Destruction	**Process Block 2:** **Air Revitalization:** Algae/Cyanobacteria: CO2 Removal Algae/Cyanobacteria: O2 Production Algae/Cyanobacteria: Nutritional Supplement Algae/Heterobacteria: SVOC Destruction
Process Block 3: **Waste & Power** Urine and Graywater Processing Blackwater and Solids Processing Microbial Fuel Cell	**Process Block 4:** **Future Higher Order Plants** Greenhouse Plugin

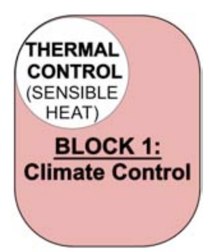
1. Humidity Control: Latent Heat –



The WW system will use an Osmotic Membrane Dehumidifier (OMD) that operates at cabin temperature. The ability to dehumidify independently of heating or cooling will provide an advantage in simplicity, mass, and power consumption. The OMD is a membrane-based system that uses osmotic potential gradients to remove water vapor from cabin atmosphere. It is essentially the same as the forward osmosis process used in the Urine/Water Process Subsystem except that it operates with higher salt concentrations and uses a gas diffusion membrane as an atmospheric contactor. An OMD uses a semi-permeable membrane to facilitate capillary condensation of water vapor and the transport of that condensed water through the membrane into a salt solution by osmosis. Here a humid gas stream is brought into contact with a semi-permeable membrane, which separates the gas stream from an osmotic (e.g., salt) solution. Liquid formed within these pores connects with liquid formed in adjacent pores, collectively forming continuous paths of liquid. These 'liquid bridges' extend across the thickness of the semi-permeable membrane and provide paths by which water can travel across the membrane. FIGURE 10 illustrates the Humidity Control subsystem.

Because the membrane is so thin, large water concentration gradients occur across the membrane. This concentration drives water transport between the humid air and the osmotic fluid. FIGURE 10 shows how the humidity control bag would function in the WW system. This figure shows the use of a highly saline solution with osmotic and gas permeable membranes to isothermally remove water form the cabin atmosphere. The subsystem uses a reverse osmosis pump to remove water from the saline solution resulting in a reconstituted saline solution.

2. Thermal Control – Sensible Heat



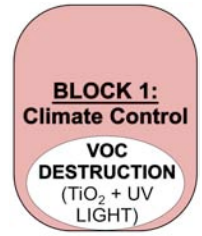
Sensible heat control will be accomplished by controlling the internal temperature of the water contained in all the WW bags. The dehumidification, air revitalization, and SVOC destruction bags will be cooled using a cool water buss and this heat will be radiated to space. The WW system provides a thermal environment that is highly buffered and largely determined by the temperature of the water contained in the water bags, acting as a heat sink to provide thermal stability throughout the crew cabin.

The primary vehicle to provide this buffering is to pump water as the cooling and heating fluid through tubing that passes through every WW bag. In this respect, the functional organization of the sensible heat thermal control system resembles the liquid cooling garment (LCG) that maintains thermal regulation for an astronaut in a space suit.

Our working assumption is that the WW team can size the surface area of the algae and humidity control subsystems with sufficient accuracy and within a manageable order of magnitude to control the cabin temperature. If that area and volume prove to be insufficient, we can add sensible heat thermal control bags to the **Climate Control Process Block 1.** Detailed calculations have not been completed yet because experimental work to measure the heat transfer of the bags in the cabin environment remains ahead of us. Ultimately measurements in microgravity are going to be required to accurately determine the thermodynamics.

3. Volatile Organic Carbon (VOC) Destruction and Removal Subsystem

A non-bag element of the Water Walls system is responsible for controlling Volatile Organic Compounds (VOC's) in the cabin environment. For this part of the system, cabin surface elements (such as the open-grid panels protecting the WW bags) are painted with, or embedded with, volatile-oxidizing nanoparticles, which use UV light or ambient light as a catalyst for volatile destruction. The option is also provided for a thermal catalytic polishing system.



The WW system will remove and destroy VOCs from the cabin atmosphere using primarily visible spectrum photo-catalytic oxidation (PCO). PCO stands at Technology Readiness Level-3 proof of concept for its ability to remove air pollution. PCO's ability to oxidize organics to carbon dioxide and water makes PCO especially attractive for treating spacecraft cabin pollutants. Depending upon the success of the planned PCO tests, the WW team anticipates the possible need to add a conventional thermal catalytic trace contaminant control system (TCCS), such as used in ISS, for final polishing of the cabin atmosphere. TiO_2 is the most popular photocatalyst employed in PCO due to the hydrophilic properties of TiO_2 and its ability to degrade a wide range of inorganic and organic compounds under irradiation of UV or near UV-light. The photo-oxidation and reduction reactions occur simultaneously in the presence of air.

G. Process Block 2 Air Revitalization and Algae Growth

The **Air Revitalization Block 2** provides CO_2 removal, O_2 production, algae or cyanobacteria growth for nutritional supplement, and SVOC destruction. Although all these processes occur in one container, the key parameters can behave like four subsystems. An important next step in the research will be to formulate algae growth cultures that are optimized for each of these several functions that may lead to separate subsystems.

1. Air Revitalization Subsystem

Carbon dioxide removal and oxygen generation occur in the algae bags. These algal bioreactors will treat all of the CO_2 generated by the crew and other biological or chemical sources. The bags will also generate the O_2 that the crew needs. Interior cabin lighting will provide light for the growth of algae in the bags, so they must be exposed to cabin illumination on at least one side. These Algae bags will also remove semi-volatile organics through symbiotic growth with aerobic bacteria that cohabit with the algae or cyanobacteria. The algae growth bags use ambient cabin light to perform photosynthesis to convert CO_2 to O_2. This illumination arrangement means that nominally, the algae growth bags will receive light on only one side, which limits the thickness of the algae culture to about 2.5cm. Installing additional lighting on the other side of the algae bag would allow a doubling of thickness, but would also require a second internal structure to support those lumieres.

Managing algae growth means equally managing algae death and disposing the resulting inert biomass or using it in some ecologically sound and productive way so that the WW system retains the benefit of the mass. As dead algae and bacteria build up in the bag the solids can be filtered out and the bags reused or the bags can be replaced with solids retained in them. These used and filled bags can provide radiation shielding (Miller, Cohen, Parodi; 2014) or soil for future higher order plants in **Process Block 4.**

Algae bags use ambient cabin light to power photosynthesis, capture CO_2, and generate O_2. The driving metric for algae's role in the air revitalization is the uptake of CO_2 that translates into carbon sequestration in algae growth. TABLE 3 shows a comparison of experimental results for CO_2 removal requirements for the volume of algae, area of gas exchange membrane, and the number of bags required to provide that area. This table uses the dimensions of 0.25m x 0.50m for the area of gas exchange membrane for the algae growth bags. The thickness of these bags when filled is 2.5cm. FIGURE 8 (above) shows the Water Walls laboratory setup to grow algae to sequester organic carbon in the experiment that is the basis for the TABLE 3 results. FIGURE 11 shows the Air Revitalization Subsystem concept of operation using algae growth bags. FIGURE 12 shows a detail of how the algae growth bag installation would be attached to the space habitat wall.

2. SVOC Destruction and Removal Subsystem

Water Walls performs semi-volatile removal and destruction using gas permeable membrane water bags. These bags may be either dedicated semi-volatile bags or a symbiotic companion function in the algae growth bags, or both. These bags allow semi-volatile organics to condense in equilibrium with the gas phase. Henry's Law predicts this equilibrium. Henry's Law predicts the extent to which a chemical separates between water and air. The functional form of Henry's Law is:

$$yi/_{xi} = Hi/_{P}$$

Where, yi and xi are the component vapor and liquid phase concentrations respectively, Hi is the Henry's Law constant (in units of pressure), and P is the pressure of the system. As the Henry's Law constant increases, the more likely a substance will volatize rather than remain in water. Compounds with Henry's law constants less than 50 will solubilize appreciably in water across a gas permeable membrane. Compounds with higher constants solubilize less well and so are more difficult to remove. Chemicals with excessively high Henry's Law constants volatize out of water quite readily and so a membrane cannot remove them. They will be removed through the separate VOC removal system that will destroy them directly from the atmosphere.

Data on SVOCs comes from the International Space Station (ISS) humidity control system. Water condensed in this system provides an indication of what the removal rates for a WW system would be. In 2009, ESA measured SVOCs in the ISS atmosphere by analyzing the condensate from the condensing heat exchanger in the Columbus module on ISS. Data from 2009 Columbus condensate water appears in TABLE 4.

Assuming that the condensation of cabin humidity achieves a Henry's law equilibrium, then the Total Organic Carbon (TOC) in the Columbus atmosphere is 122 mg/kg of water and the ammonia, as ammonium, is 29 mg/kg of water. After removing the ammonia and organics from the cabin atmosphere in the condensate water, these contaminants can be captured using biological or physical chemical approaches. Biological SVOC destruction techniques involve heterobacteria or other opportunistic organisms living in the Algae bags. Physical/chemical techniques are primarily wet oxidation such as used in the Volatile Removal assembly on ISS. Regardless of which treatment is applied, the individual solubility's of each compound will set the rate-limiting step.

TABLE 3. Comparison of Algae Bag Area Estimates for Water Walls for Anabaena Algae and Synechococcus Cyanobacteria

Source	Species	Volume/ Crewmember / Day for CO_2 in liters	Volume/ Crewmember/ Day for CO_2 in m^3	Area in meters at 2.5cm Bag Thickness	Algae Bags at 0.225m x 0.45m Membrane size (.101m^2)
Rocco L. Mancinelli	Anabaena	777.3	0.7773	44.00	436
Rocco L Mancinelli	Synechococcus	166.7	0.1667	9.60	95

H. Process Block 3 Waste and Power

Wastewater Processing encompasses urine, condensate, blackwater/solids, and hygiene/ laundry/ graywater. The degree of closure of the water loop, including wastewater treatment, is a bellwether for the Water Walls system design.

Water recycling in the WW system uses a technology that is similar to the commercially available Hydration Technology Innovations (HTI) X-Pack® water treatment bag. The X-Pack® is a forward osmosis (FO) water treatment bag that can produce clean drinking

TABLE 4. Semi-Volatile Organic Compound measurements using the condensing heat exchanger in ISS Columbus module.

Compound	Columbus Crew Latent Condensate in mg/L	Percentage S-VOC in Humidity by Mass
Ammonium	29	0.0029
Total Inorganic Carbon	97	0.0097
Total Organic Carbon	122	0.0122
Total Carbon	219	0.0219

water from seawater, urine, or other wastewater. The X-Pack ® is currently marketed for this application and is sold worldwide for commercial/recreational use, disaster relief, and military use. Referring back to FIGURE 1, the X-pack® is the FO bag shown.

In-house testing demonstrated the ability to treat wastewater in an X-PackTM bag with a water recovery ratio of 90%. The testing also measured flux rate. Flux rate is important as it defines the amount of membrane required to treat the wastewater on a given mission. The maximum flux rate of water in the X-Pack® is 3.5 L/m2hr when treating wastewater and 0.3 L/m2hr when treating the blackwater/solid simulated fecal ersatz. Flux rates decrease as a function of time – the longer the X-Pack operates, the slower the flux.

The XPack® bag includes two ports. The **green port** serves two purposes: to receive the osmotic agent that creates the solvent/solute disequilibrium that drives osmosis and to pour out the purified water from that side of the white interior osmotic membrane. The **red port** connects to the opposite side of the membrane and it is the port through which to add seawater or wastewater to the XPack bag.

However, there are several alternate Water Walls system designs that can process some – but not all – of these fluids. For the purposes of simplicity and clarity, this section addresses two of the alternatives:

- Partially Closed Water Loop that excludes hygiene/laundry/graywater from the mix, versus
- Maximally Closed Water loop that includes all the fluids.

TABLE 5. presents an overview of closure issues in urine and wastewater processing systems. This table and the accompanying discussion use the terms partially closed and maximally closed in lieu of the terminology in Hanford (2006) for early habitat and mature habitat, respectively.

TABLE 5. Comparison of Wastewater Treatment Alternatives for Partially Closed and Maximally Closed Water Loops

Criteria	Partially Closed Water Loop (PCWL)	Maximally Closed Water Loop (MCWL)	Remarks
Duration	< ~ 1 Year	>~ 1 Year	Once the WW system is perfected, this distinction will fade.
Typical Mission	Mars Transit, Asteroid Rendezvous	ISS, Lunar or Planetary Base	
"Maturity"	"Start-up" condition	"Mature" condition	The PCWL is sometimes called a "start-up" system because its equilibrium operating state resembles the initial state of an MCWL.
Urine	YES	YES	
Condensate	YES	YES	From humidity removed by latent thermal control subsystem.
Blackwater/Solids	NO	YES	May or may not include dilution with graywater.
Graywater	**NO**	YES	

TABLE 5. presents a general, qualitative comparison of these two alternatives. It shows the approximate process durations and displays the terminology that researchers in the field use to describe this comparison.

TABLES 6 and 7 provide the details for the differences between the Maximally Closed Water Loop and the Partially Closed Water Loop. They show cost estimates for a day in space for support of an astronaut using the price that SpaceX offers for the launch of payload from the Earth to the ISS at $5359/kg. TABLE 6 shows the mission profile for partially closed water loop for a duration of a year or less. Comparing this table to the MCWL table shows the dramatic difference in total mass for the Graywater/Washing functions. TABLE 7 shows a mission profile for a duration longer than one year including clothes washing, dish washing, and shower for personal hygiene. This profile shows the potential exists to achieve 100% closure of consumables.

TABLE 6. Partially Closed Water Loop for Space Missions

Partially Closed Water Loop (PCWL) in Space: Hygiene Water > Hand & Face Wash Water

Cost of Launch in SpaceX Dragon Capsule per kg $5,359

Astronaut Daily Inputs

	Mass	Percent	Cost in $
METABOLIC INPUTS/CONSUMED GAS & SOLIDS			
Oxygen	0.84	11.4%	$4,502
Food Solids	0.62	8.4%	$3,323
CONSUMED GAS & SOLIDS SUBTOTAL	1.46	19.9%	$7,824
CONSUMED+BASELINE WATER			
Water in Food	1.15	15.7%	$6,163
Food Prep Water	0.79	10.8%	$4,234
Drink	1.62	22.1%	$8,682
Flush Water	0.50	6.8%	$2,680
CONSUMED+BASELINE WATER SUBTOT	4.06	55.3%	$21,758
GRAYWATER/WASHING			
Hand & Face Wash Water	1.82	24.8%	$9,753
GRAYWATER/WASHING SUBTOTAL	1.82	24.8%	$9,753
TOTAL	**7.34**	100.0%	

Astronaut Daily Outputs

	Mass	Percent
METABOLIC OUTPUTS		
CO2	1.00	12.6%
Respiration & Perspiration Water	2.28	28.7%
Urine	1.50	18.9%
Feces Water	0.09	1.1%
Sweat Solids	0.02	0.3%
Urine Solids	0.06	0.8%
Feces Solids	0.03	0.4%
METABOLIC OUTPUTS SUBTOTAL	4.98	62.6%
SYSTEM OUTPUTS		0.0%
Hygiene Water	2.41	30.3%
Other Latent Water	0.65	8.2%
Flush Water	0.50	6.3%
SYSTEM OUTPUTS SUBTOTAL	3.56	44.8%
TOTAL	**8.54**	107.4%

Theoretical Percent Closure **85.95%**

TABLE 7. Maximally Closed Water Loop for Space Missions

Maximally Closed Water Loop (MCWL) in Space

Cost of Launch in SpaceX Dragon Capsule per kg $5,359

Astronaut Daily Inputs

	Mass	Percent	Cost in $
METABOLIC INPUTS/CONSUMED GAS & SOLIDS			
Oxygen	0.84	2.7%	$4,502
Food Solids	0.62	2.0%	$3,323
CONSUMED GAS & SOLIDS SUBTOTAL	1.46	4.7%	$7,824
CONSUMED+BASELINE WATER			
Water in Food	1.15	3.7%	$6,163
Food Prep Water	0.79	2.6%	$4,234
Drink	1.62	5.3%	$8,682
Flush Water	0.50	1.6%	$2,680
CONSUMED+BASELINE WATER SUBTOTAL	4.06	13.2%	$21,758
GRAYWATER/WASHING			
Hand & Face Wash Water	1.82	5.9%	$9,753
Shower Water	5.45	17.7%	$29,207
Clothes Wash Water	12.50	40.7%	$66,988
Dish Wash Water	5.45	17.7%	$29,207
GRAYWATER/WASHING SUBTOTAL	25.22	82.0%	$135,154
TOTAL	**30.74**	**100.0%**	

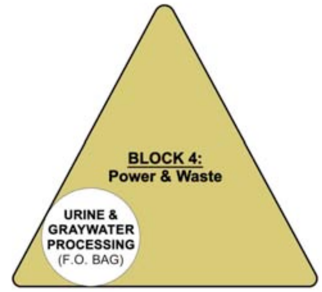
Astronaut Daily Outputs

	Mass	Percent
METABOLIC OUTPUTS		
CO2	1.00	3.3%
Respiration & Perspiration Water	2.28	7.4%
Urine	1.50	4.9%
Feces Water	0.09	0.3%
Sweat Solids	0.02	0.1%
Urine Solids	0.06	0.2%
Feces Solids	0.03	0.1%
METABOLIC OUTPUTS SUBTOTAL	4.98	16.2%
SYSTEM OUTPUTS		
Hygiene Water	6.68	21.7%
Clothes Wash Water	11.90	38.7%
Clothes Wash Latent Water	0.60	2.0%
Other Latent Water	0.65	2.1%
Dish Wash Water	5.43	17.7%
Flush Water	0.50	1.6%
SYSTEM OUTPUTS SUBTOTAL	25.76	83.8%
TOTAL	**30.74**	100.0%

Theoretical Percent Closure **100.00%**

1. Urine and Graywater Processing Subsystem

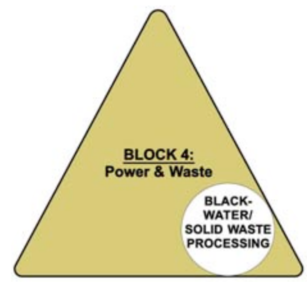
WW uses Forward Osmosis (FO) to process urine and graywater (wash water) into clean water. In wastewater treatment applications where the solvent is water and the solutes are the contaminants, the semi-permeable membrane is designed to maximize the flux of water and the rejection of contaminants. The wastewater feed passes to one side of the membrane and the osmotic agent, such as salt water, passes to the other. The osmotic agent (OA) can use any solute with an osmotic pressure higher than that of the feed. The OA should not permeate through the membrane. Typically, sodium chloride or sugar afford inexpensive and readily available OAs.



Water Walls will adapt the "white membrane" technology in the XPack to become part of an integrated subsystem within a larger integrated system. FIGURES 5 and 7 suggest this integration. The Urine and Graywater Processing Subsystem produces clean water for the crew, for algae/cyanobacteria/heterobacteria growth, and for future greenhouse plant growth. As byproducts, this subsystem produces ammonium brine that goes to the blackwater/solid waste processing subsystem. The Urine and Graywater Subsystem also creates the byproducts $CaSO_4$ and $CaCO_3$, for which the WW system does not have a particular use at this time, but which could be useful for other crew projects or activities.

2. Blackwater and Solids Processing Subsystem

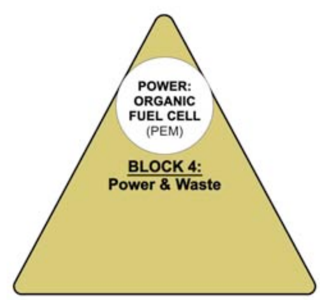
Solid waste treatment is the processing and dewatering of solid wastes to produce structural elements that aid in radiation protection. It is completed in several steps. The first step is to collect the concentrated brines produced from the water treatment. The next step is to combine these brines with feces and wet trash and placed in a FO bag. The third step is to add a concentrated salt solution to dewater these solids by drawing the water out of them across the FO membrane. After dewatering the solids, biological composting can begin. The result is a biologically stable dry solid. The final step is to dry this solid fully dried by venting to the vacuum of space or through a vacuum pump. FIGURE 13 illustrates this sequence of steps.



The WW project also introduces a new set of potential risks and thus new challenges with regard to hazardous waste handling. Initiation of use of the WW system requires the transfer of wastes into the membrane-integrated bags. Transfer of wastes could occur manually, by directly urinating and defecating into the system bags, or through automated plumbing systems. Each transfer option creates a potential risk. The manual method of waste transfer requires contact with human wastes (feces, urination, other trace bodily fluids), and increases the risk for the introduction of potential biological hazards into the spacecraft environment via condensation and aerosolization. While risks are increased with the manual methods of transfer, the materials required for use of the WW system are limited to the bags, a draw solution and the waste produced by the user. Automated transfer using a plumbing system would reduce the risks associated with contact and handling of wastes, but could present other issues, such as clogging, leaks, contamination of the clean water produced, or system failure. Automated transfer requires a larger amount of materials, increasing the flight mass of the system.

3. Bioelectrochemical System (BES)

Energy from waste systems are being developed to provide localized low power sources for the WW system to eliminate the need for complicated wiring harnesses to provide power to sensors, valves, and even small pumps. This approach provides localizes power generation adjacent to the power consumer. So, for instance a low power valve or sensor could be powered by solid waste in an adjacent bag. A sensor could be continuously powered. A higher powered intermit operation actuator, such as a valve, would be powered by a battery that was then recharged. In either case, a bioelectrochemical system can provide this power. The Water Walls project has baselined a Microbial Fuel Cell (MFC) to provide this utility. Running the MFC on human waste would provide the power source.



Microbial fuel cells produce an electrical current. It involves two electrode chambers, an anode and a cathode, that are separated by a proton exchange membrane (PEM). The design and components of each electrode chamber are dependent on the desired result or product of the overall system, and can involve microbial cultures or communities, electrolytes, electrochemical reactions, and water.

I. Subsystem Operating Concepts

The WW team prepared a set of renderings to illustrate examples of how selected, representative WW subsystems would be installed and operated. These Vectorworks CAD drawings explicate the subsystems as follows:

FIGURE 10: Humidity (Latent Heat) Climate Control Subsystem,
FIGURE 11: Air Revitalization and Algae Growth Cycle Subsystem,
FIGURE 12: Installation of the Algae Bags in a Habitat Module, and
FIGURE 13: Wastewater Treatment Cycle Subsystem.

These "storyboards" are largely self-explanatory, but more detailed explanations follow below. They reveal the emphasis upon achieving commonality among the key components: the osmotic membrane WW bags and the internal sensible heat control system for each one.

4. Water Walls Humidity-Control Bag Cycle

FIGURE 10 shows the Humidity (Latent Heat) Control Subsystem. Humidity-Control Water Walls Bags have an outer front membrane permeable to water vapor. As the humid cabin airstream flows over the bags, the water vapor passes through the membrane and condenses into the saturated salt brine solution within the bag. Over time, the added condensate dilutes the brine, so the diluted solution is periodically passed through a manual reverse osmosis (RO) pump for desalination. The fresh water from the condensate is recycled back for habitat use, while the residual salts are returned to refresh the saline brine for future bag reuse. A contiguous cooling tube running between the bags removes the latent heat of condensation, which is released into deep space via the habitat radiator.

5. Water Walls Air Revitalization Bag Cycle

FIGURE 11 shows the Air Revitalization and Algae Growth Subsystem. Air Revitalization Water Walls Bags serve the multi-purpose role of sequestering CO_2 and releasing O_2, while also removing semi-volatile organic compounds (SVOC's) from the cabin air stream. The Air Revitalization Bags are primed with either saline or fresh water, and incubated with freshwater algae, freshwater cyanobacteria, or marine (saltwater) cyanobacteria. Resulting population growth fills these bags to capacity. When exposed to cabin lighting, these aquatic, photosynthetic organisms sequester CO_2 from the airstream and release O_2 back into the cabin. At the end of the life cycle, dead cell mass starts to accumulate in the bags. At this point, remaining mature, healthy cells will be distributed amongst new bags to start the next generation of algae/cyanobacteria growth. The remaining spent bag can then either be transferred from the functional bag area to the rear layer of Water Walls bags to serve as additional radiation protection, or the water can be filtered through the forward osmosis (FO) membrane to the rear bag chamber using a saline draw, the water can be recycled back into the habitat system, while the spent cells are removed, and the bag is cleaned for reuse. Harvested algae and edible species of cyanobacteria (spirulina) can provide a high-nutrient supplement for the crew, especially critical on long-duration missions. Water Walls Bags containing algae or an algae/heterobacteria mix will intrinsically provide SVOC destruction. According to Henry's Law, the SVOC's moving through the air stream across the bag's gas permeable membrane will solubilize into the water. Organisms living in the algae bags will break down these contaminants. Minimal amounts of breakdown products from SVOC's should not hinder the fundamental process cycles, but bags will be monitored for any toxic impact from SVOC destruction.

6. Water Walls Bag Installation at Habitat Module Wall

FIGURE 12 shows the installation of the Algae Bags in a Habitat Module. The standard, modular unit comprising this passive system is the Water Walls Bag; a rectangular polyethylene bag with one or more specialized internal or external membranes. Bags have input and output ports on both sides, and can be linked in series as necessary. Individual WW bags are secured within snapped mesh pockets (which allow light and air to reach the bags) and the pockets are arrayed to form panels. Panels are fixed to the installation grid at the habitat structure and are installed in multiple layers (with airspace in between bag layers as necessary) to increase overall radiation shielding capability. Bag panels are offset from one layer to the next to provide consistent depth of shielding. These soft panels are then covered by a hard, protective, open-grid panel system. The grid panels, as well as the bag panel layers behind them, are hinged at one edge to facilitate access. The modular nature of the bags allows for flexible placement within the habitat, but the majority of the bags will be placed at the periphery to provide continuous radiation shielding for the crew. Additional bags can be placed around a storm shelter.

7. Water Walls Wastewater Bag Cycle

FIGURE 13 shows the Wastewater Treatment Cycle Subsystem Water Walls Wastewater Bags process graywater and blackwater from the crew and habitat systems, ultimately providing recycled fresh water for habitat reuse, and residual waste mass for habitat radiation protection. Graywater-filled Water Walls Bags use a highly concentrated saline draw to pull water across the FO membrane, leaving behind concentrated brine. Accumulated water dilutes the draw-side solution, so it is passed through a reverse osmosis (RO) pump, which separates the salt content from the water. The freshwater is sent on for UV treatment and then recycled back for habitat reuse, and the salt is returned to replenish the saline draw in the FO bag. The Graywater Bag is re-used numerous times, until the front compartment of the bag is filled with concentrated brine. This brine is then transferred to a Blackwater Bag, filled with crew solid waste. The bag contents are left to decompose until no longer biologically active. The bag is then passed through a vacuum chamber with odor control to completely dry the waste. The Water Walls Bag containing the resultant solid dried mass can then be placed, out of sight, at the periphery of the cabin to provide additional radiation protection.

VI. Water Walls Installed in a Space Habitat

The architectural success of WW comes with its own imperatives: to integrate WW seamlessly into the living and working environment, and then to design the total spacecraft around that environment to best support the crew.

Conventional approaches to space habitat design, whether for a space station or a lunar-planetary base, begin from a pressure vessel structure for an aeroshell or space module. The designers then subdivide the interior space to stuff in all the functions, with the utilities routed circuitously -- with difficult accessibility -- through standoffs, beneath floors, and behind wall panels. Installation of all equipment becomes an exercise in retrofitting a volume designed without any consideration for the crew's needs (Skylab, Mir, ISS modules).

This approach is to design the module from the inside out: the life support architecture comes first. Architecture serves as the integrative discipline, coordinating all crew, engineering, and operational aspects of the ECLSS into the whole. Integrating all the human support functions into the spacecraft or habitat from the beginning of the design process substantially reduces development risk and DDT&E cost, because it avoids needing to make a flood of design changes late in outfitting.

FIGURES 14 and 15 present an existence proof that it should be possible to install a system of Water Walls bags, including all the subsystems and their various component bag types into a full-featured space habitat. This CAD model adopts the Bigelow Aerospace 330 TransHab type module because geometrically it is about the simplest habitat geometry in the literature. The cylindrical shape allows the application of a square grid rolled or circumscribe onto the interior surface. FIGURE 14 shows a transverse section through the BA 330, revealing the concentric layers of Water Walls membrane bags, on the outer side of the attachment mesh. FIGURE 15 shows a longitudinal section of the BA 330, with the Water Walls bags on the end panel of the module. Unlike an ISS module with its frustoconical end caps or Skylab with its oblate ellipsoidal end domes, the B330 has simple flat, circular end panels. This sample configuration allows the team to address the full range of Water Walls architectural issues without needing to battle any special configuration challenges, such as for example, the Zvezda module on ISS would pose with its several different diameters and frustoconical mid-section.

The objective for the Habitat Architectural research is to achieve the flexible integration of WW into a spectrum of space habitat configurations for long duration space travel. The long-term research approach is to model habitat architecture computationally in Excel, and in the CAD program Vectorworks using its built-in Building Information Modeling (BIM) database capabilities. In a BIM model, every object comes with its own data structure; system integration occurs among the common variables, functions, or procedures within those data structures.

The development of this fundamental CAD model enables the WW team members to examine the issues that arise for installing Water Walls in the space living and working environment. Each Process Block will probably need to be assigned to its own area or sector in the interior of the habitat. These Process Blocks and their respective subsystems will need to be connected together with tubing, pumps, valves, and sensors to provide the ability to move WW fluids and masses around the system from where they are produced to where they can be processed or consumed. A common data system will provide the built-in automation and intelligence to operate this system. Demonstrating simplicity and ease of installation is a step to gaining acceptance for WW for long duration missions such as Phobos.

VII. Conclusion

The results that flow from the Water Walls project address the architectural and functional organization of a prospective passively based life support system. This architecture and planning prepares for the consolidation, integration, and simplification of subsystems and components within that system, and its application to human spacecraft and space habitat architectural design. The key points that derive from the WW study include: the pyramidal hierarchy from the functional flow concept down to the component level, the consolidation of subsystems into the process block level, the subsystems themselves and the criteria that argue for either centralization or decentralization of their functions, discrete versus distributed subsystems, commonality among like components, and radiation shielding "grown" from WW materials.

The Water Walls Phase I study led the team to two broad sets of evaluations. The first set identified issues in mass balance and mass balance sensitivities. The second set defines the Technology Readiness Levels (TRLs) achieved by the end of the study.

TABLE 8. Water Walls Mass Balance Sensitivities

Technology	Affects Mass Balance	Involves Nitrogen Economy	Incurs Mass Losses	Remarks
Habitat-Wide/Cross-Cutting Technology – Living and Working Environment				
Habitat Architecture	**No**	**No**	**No**	Goal: Integrate WW seamlessly with Habitat.
Radiation Protection	**No**	**No**	**No**	Goal: Apply mass-flow end product as "non-parasitic shielding" to the habitat.
Process Block 1: Climate Control – Requires Forced Air Flow				
Humidity Control (Latent Heat)	**Yes**	**Yes**	**No**	Uses brine and captures moisture from air to return as condensate.
Temperature Control (Sensible Heat)	**No**	**No**	**No**	Temperature in FO bags affects all Water Walls processes.
VOC Destruction	**No**	**No**	**No**	Uses doped TiO_2 under ambient or ultraviolet light.
Process Block 2 – Air Revitalization – Uses Passive Air Flow				
CO_2 Removal	**Yes**	**Yes**	**No**	Sequesters carbon in algae or cyanobacteria.
O_2 Production	**Yes**	**Yes**	**No**	Liberates O_2 by photosynthesis. ¿True for cyanobacteria?
Nutritional Supplement Production	**Yes**	**Yes**	**Yes**	Converts complex carbon compounds to food.
SVOC Destruction	**No**	**No**	**No**	Uses algae / heterobacteria mix.
Process Block 3 – Energy and Waste – Sealed Bag / No Contact with Air				
Urine Processing	**Yes**	**Yes**	**No**	Reuses H_2O and produces brine.
Blackwater/ Solid Waste Processing	**Yes**	**Yes**	**No**	Uses brine. Produces fertilizer for algae and fuel for fuel cells.
Solid Waste End Product	**No**	**No**	**Yes**	Fecal simulant dried and used in radiation shielding experiment
Organic Fuel Cell	**Yes**	**Yes**	**Yes**	Separate large project at Ames we are tracking closely.

A. Mass Balance Sensitivity

For the Mass Balance Sensitivity table, the three parameters for this evaluation are whether the process affects mass balance in the WW system, if it involves the nitrogen economy or cycles within the system, and whether it incurs mass losses to the system during a process cycle or at its end. Table 8 presents the technologies that constitute the WW system concept with respect to these parameters. The processes that affect Mass Balance include

Humidity Control, VOC Destruction (CH4, and NH_3 are a primary contaminants), CO2 Removal, O2 Production, Nutritional Supplement Production, Uribe Processing, Blackwater/Solid Waste Processing, and Organic Fuel Production. The second parameter for processes that involve the nitrogen economy include all the Mass Balance sensitive processes, plus SVOC Destruction and the solid waste end product. Finally, the third parameter is mass losses from the system. Identifies processes by which mass is consumed as energy or removed rom the system: Nutritional Supplement Production in the Air Revitalization Process Block in the form of edible algae, and in the Energy and Waste Process Block, the removal of solid waste end product and organic fuel cell operations that "burn" processed blackwater/solid waste.

TABLE 9. Water Walls Technology Readiness Levels (TRL) Status

Technology	TRL 1 Basic Principles Observed	TRL 2 Concept Formulation	TRL 3 Proof of Concept	Remarks
Habitat-Wide/Cross-Cutting Technology – Living and Working Environment				
Habitat Architecture	√	√		**Phase I** showed how WW bags might attach to habitat walls.
Radiation Shielding	√	√		**Phase I** beam-tested fecal simulant at 3 energies.
Process Block 1: Climate Control Subsystems – Mostly Requires Forced Air Flow				
Humidity Control (Latent Heat)	√			**Phase I** component idea. Returns moisture from air as condensate.
Temperature Control (Sensible Heat)	√	√		**Phase I** component approach is similar to EVA Liquid Cooling Garment (LCG).
VOC Destruction	√			Commercial applications exist, but not for closed spacecraft air.
Process Block 2 – Air Revitalization Subsystems – Uses Passive Air Flow				
CO_2 Removal	√	√		**Phase I** Opticell Experiments establish baseline.
O2 Production	√			**Phase I** Opticell Experiments establish baseline.
Nutritional Supplement Production	√			Commercial products available, but not necessarily with the species in these subsystems.
SVOC Destruction	√			Commercial systems exist, but not enclosed in an FO bag.
Process Block 3 – Energy and Waste Subsystems – Sealed Bags/No Contact with Air				
Urine Processing	√	√	√	**Pre-Phase I** Flight experiment on STS-135.
Blackwater/ Solid Waste Processing	√			Waste treatment processes are well established, but not in an FO bag.
Solid Waste End Product	√	√		**Phase I** fecal simulant used in radiation shielding experiment.
Organic Fuel Cell	√			Uses waste from solid waste flow.

B. Technology Readiness Levels

TABLE 9 presents the TRLs achieved for each of the WW technologies at the completion of the study. All technologies achieved TRL-1. The technologies that made progress at TRL-2 Concept Formulation include Habitat Architecture, Radiation Protection, Temperature Control (sensible heat), O_2 Production, and CO2 Removal. The Urine Processing achieved full TRL-3 Concept formulation by virtue of its 2011 flight experiment using ersatz urine simulant.

C. Looking Ahead to Phase II

These results show that Water Walls is solidly on the development path. What they also indicate is that the WW Project must bring all the constituent technologies up to a level where it is feasible to model mass flows among within the subsystems and between them, leading to the ability to calculate the mass balances in the total system.

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References

Aron, Jacob; Grossman, Lisa (2013, March 1). "Mars trip to use astronaut poo as radiation shield," *New Scientist*. http://www.newscientist.com/article/dn23230-mars-trip-to-use-astronaut-poo-as-radiation-shield.html, retrieved 5 March 2013.

Cohen, Marc M.; Flynn, Michael T.; Matossian, Renée L. (2012 May). Water Walls Architecture: Massively Redundant and Highly Reliable Life Support for Long Duration Exploration Missions (GLEX-2012.10.1.9x12503). *Global Space Exploration Conference (GLEX)*, Washington, DC, USA, 22-24 May 2012. Paris, France: International Astronautical Federation.

Cohen, Marc M.; Matossian, Renée L.; Mancinelli, Rocco L.; Flynn, Michael T. (2013 July). Water Walls Life Support Architecture (AIAA 2013-3517). 43rd International Conference on Environmental Systems (ICES), Vail, Colorado, USA, 14-18 July 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Flynn, Michael T.; Delzeit, Lance; Gormly, Sherwin; Hammoudeh, Mona; Shaw, Hali; Polonsky, Alex; Howard, Kevin; Howe, A. Scott; Soler, Monica; Chambliss, Joe (2011 July). Habitat Water Wall for Water, Solids, and Atmosphere Recycle and Reuse (AIAA 2011-5018). *41st International Conference on Environmental Systems (ICES)*, Portland, Oregon, USA, 17-21 July 2011. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Flynn, Michael T.; Soler, Monica; Shull, Sara; Broyan, James Lee, Jr.; Chambliss, Joe; Howe, A. Scott; Gormly, Sherwin; Hammoudeh, Mona; Shaw, Hali; Howard, Kevin (2012 July). Forward Osmosis Cargo Transfer Bag (AIAA 2012-3599). *42nd International Conference on Environmental Systems (ICES),* San Diego, California, USA, 15-19 July 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Miller, Jack; Cohen, Marc M. (2014, July). Water Walls Radiation Shielding: Preliminary Beam Testing of Fecal Simulant (AIAA-2014-ICES-26) *in press. 44th International Conference on Environmental Systems,* 13-17 July 2014, Tucson AZ. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Nabity, James A.; Andersen, Erik W.; Engel, Jeffrey R.; Wickham, David T.; Fisher, John W. (2008). Development and Design of a Low Temperature Solid Waste Oxidation and Water Recovery System, (SAE 2008-01-2052).

National Research Council (2012). NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, Washington DC: National Academies Press.

Wignarajah, Kanapathipillai; Litwiller, Eric; Fisher, John W.; Hogan, John (2006, July). Simulated Human Feces for Testing Human Waste Processing Technologies in Space Systems (SAE 2006-01-2180), 36th *International Conference on Environmental Systems (ICES)* Norfolk VA, USA 17-20 July 2006. Warrendale PA, USA: Society of Automotive Engineers.

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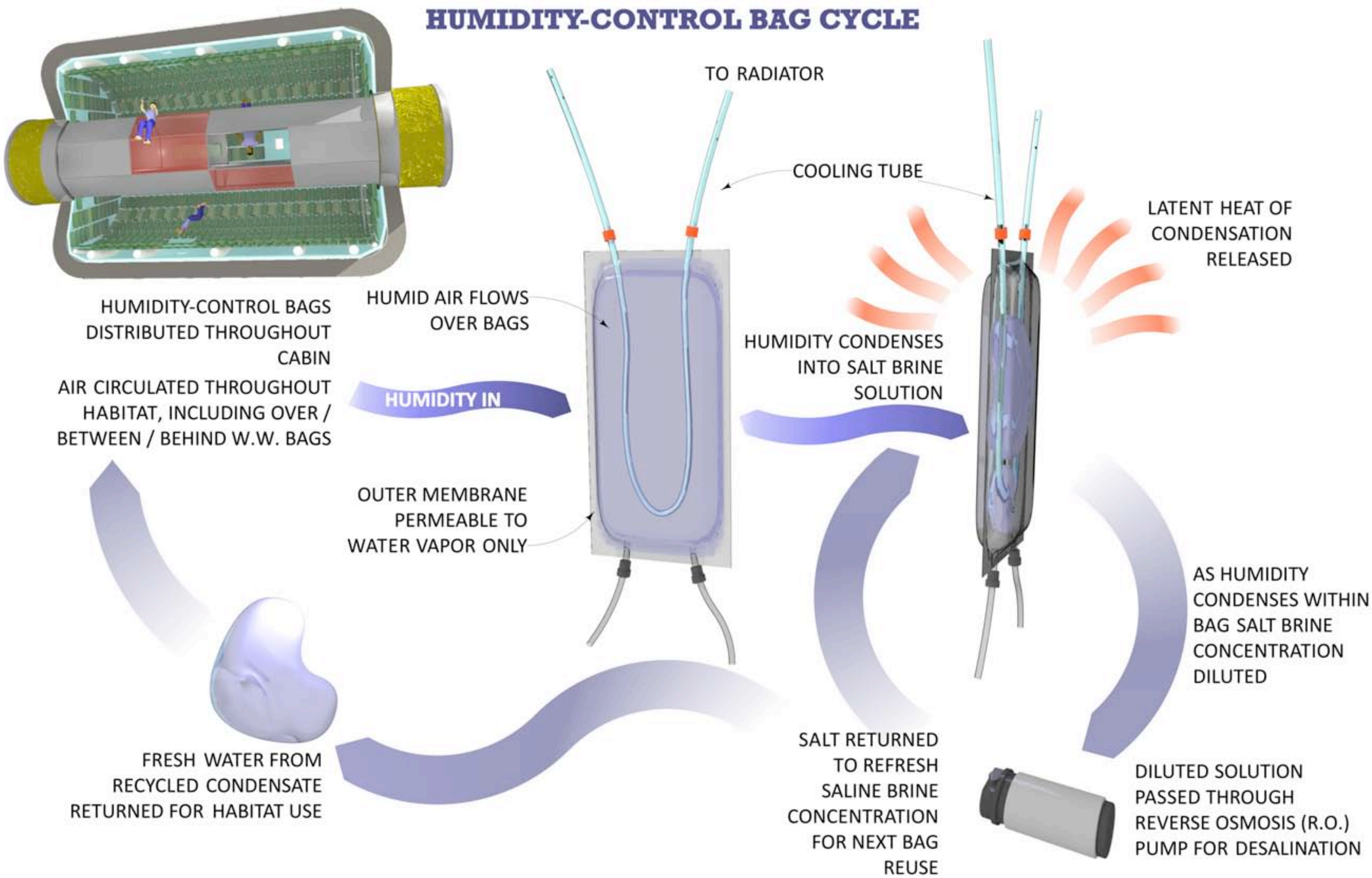

FIGURE 10. Humidity Control Subsystem – Humidity Control Bag Cycle within the Climate Control Process Block. Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

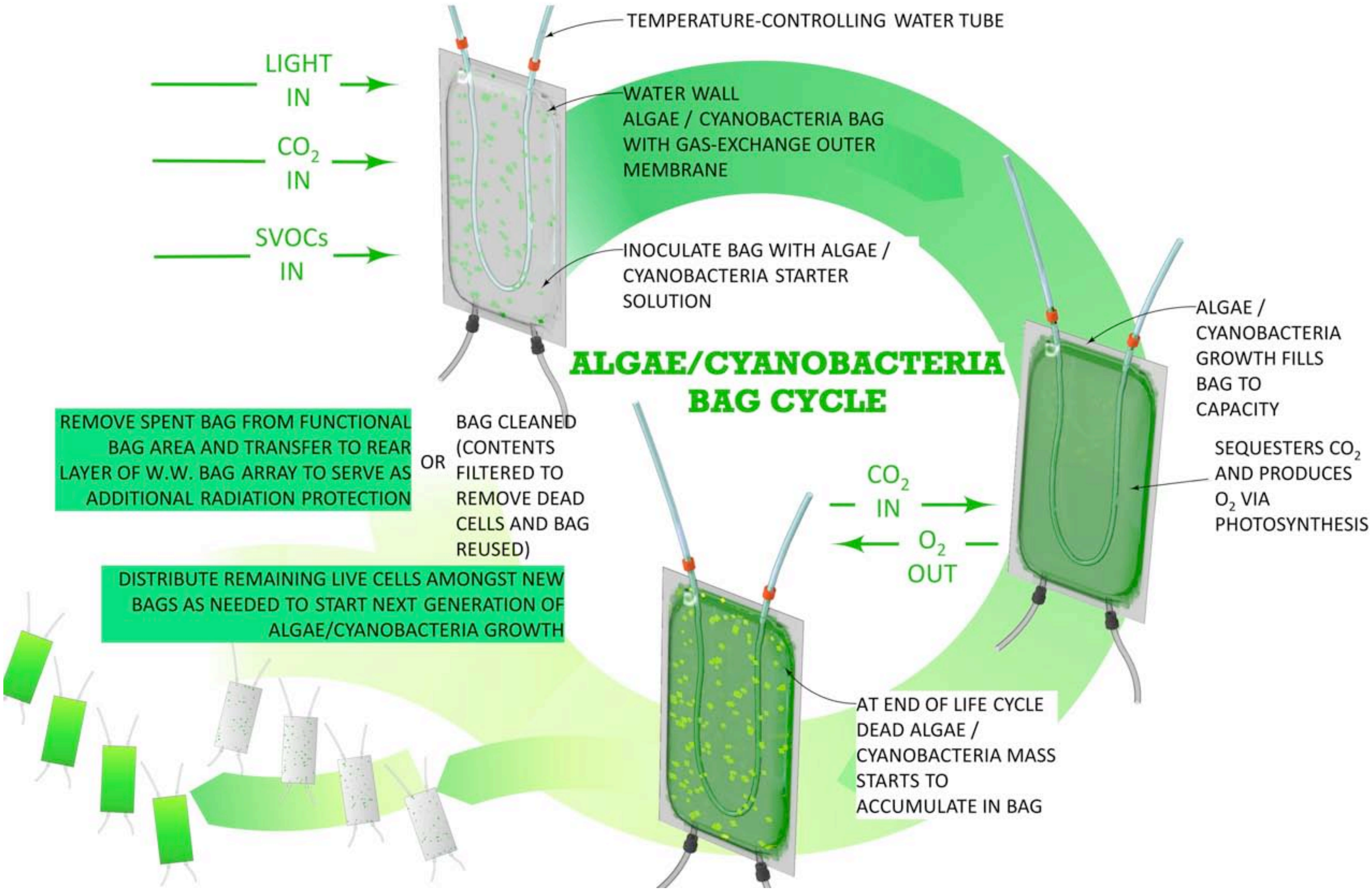

FIGURE 11. Air Revitalization Subsystem -- Algae Growth/Cyanobacteria Growth Cycle. Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

FIGURE 12. Installation of the Air Revitalization / Algae Growth Subsystem in a Habitable Space Module. Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

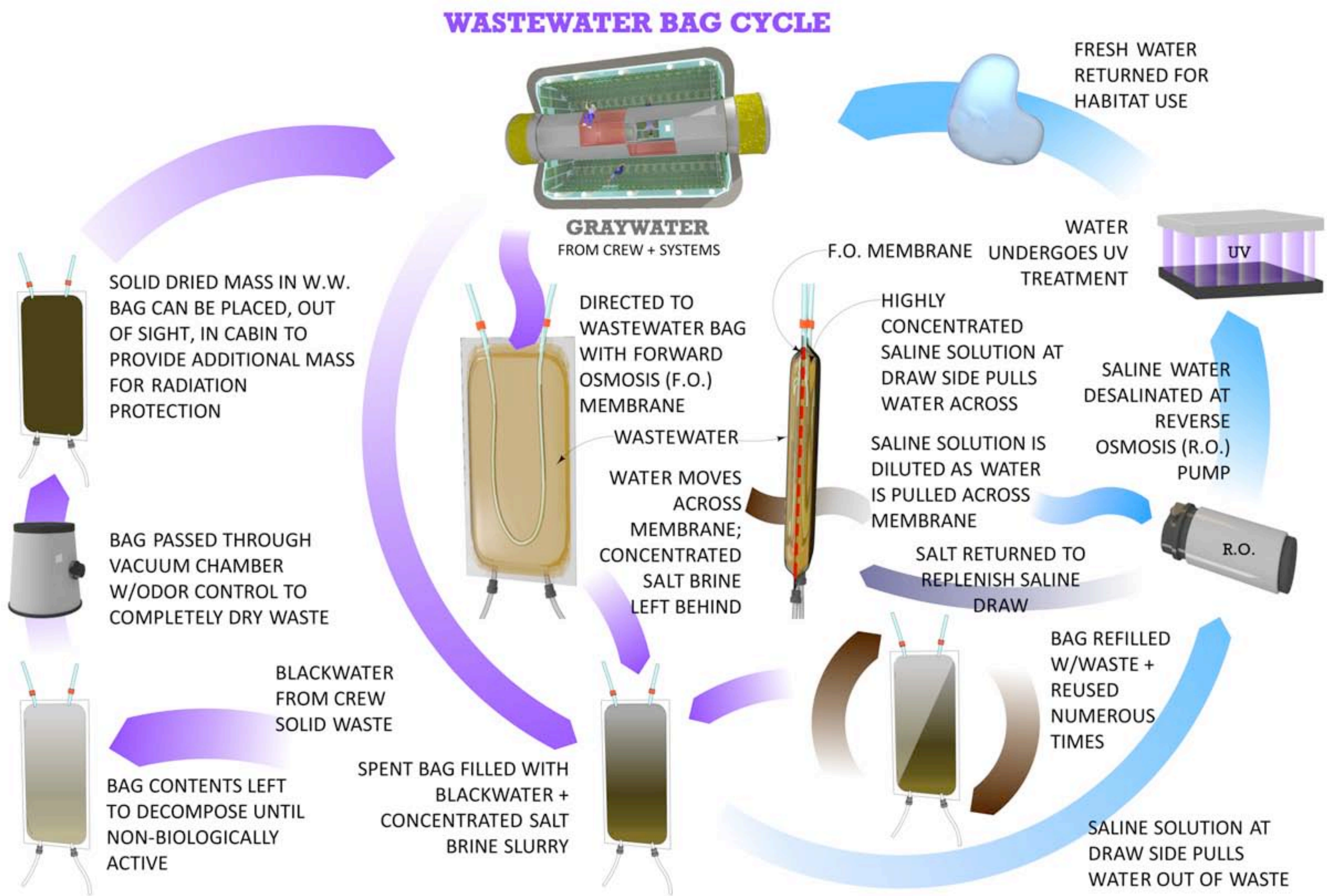

FIGURE 13. Blackwater/Solids Processing Subsystem in the Wastewater Treatment Cycle. Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

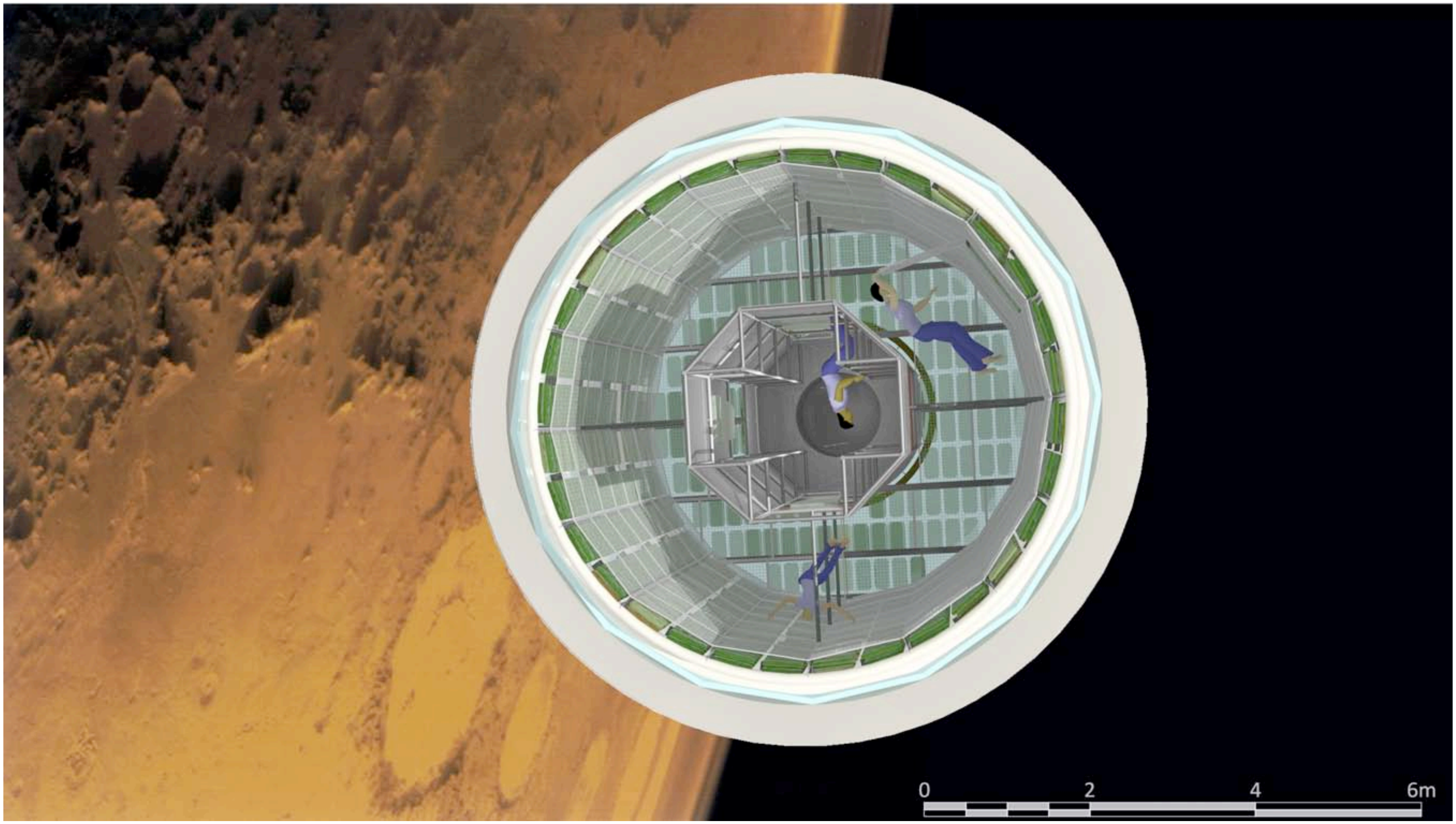

FIGURE 14. Transverse Section through a Bigelow 330 (TransHab type) space habitat, showing two layers of Water Walls Air Revitalization Bags installed around the inside perimeter of the cylindrical wall and the flat circular end walls of the inflatable pressure vessel. This view also shows the rigid center "axle" truss that serves as a circulation corridor and utility routing channel. Drawing Credit: François Lévy.

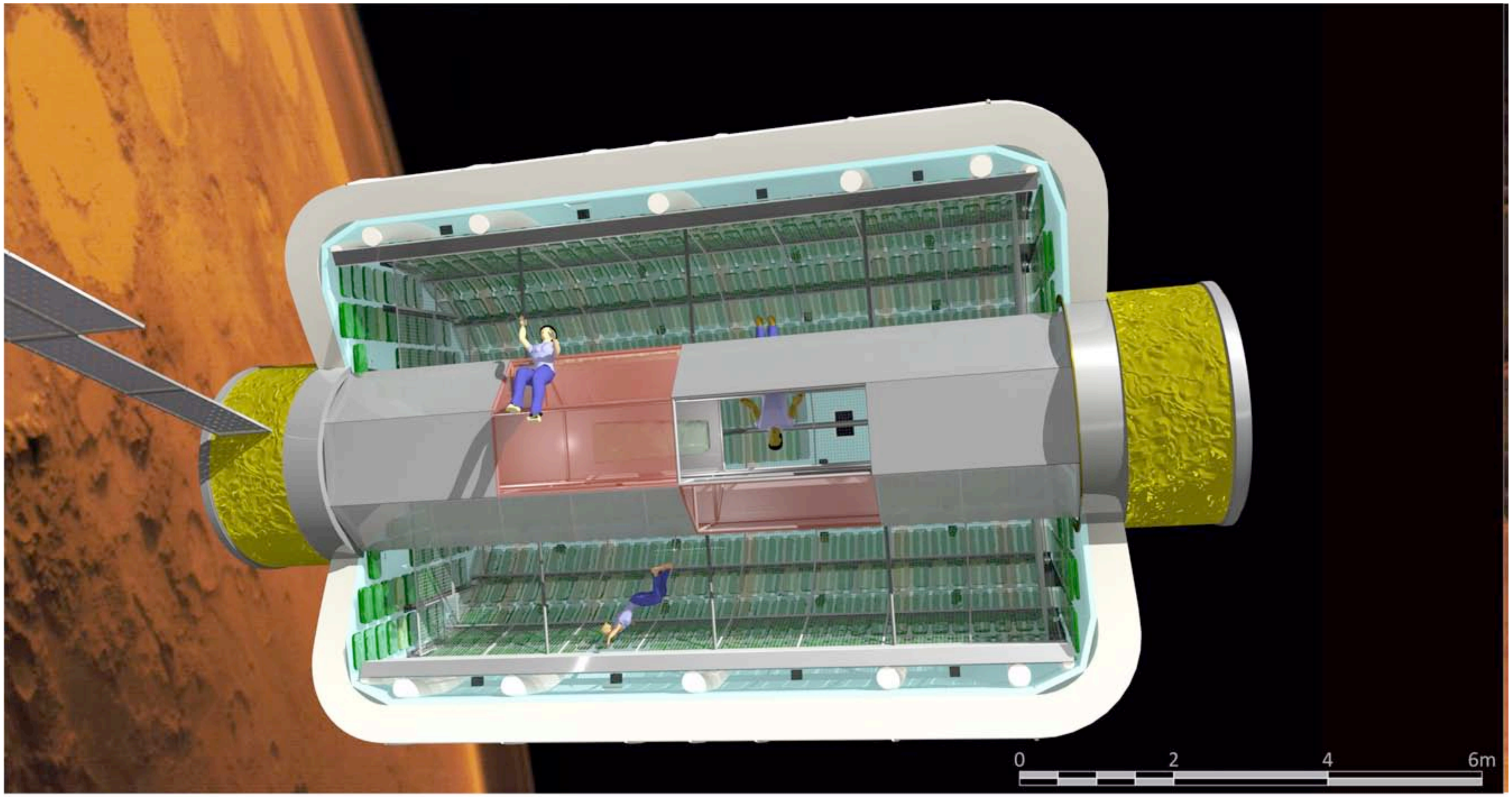

FIGURE 15. Longitudinal Section through a Bigelow 330 (TransHab type) space habitat, showing Water Walls Air Revitalization Bags installed around the inside perimeter and end walls of the inflatable pressure vessel. The center "axle" truss is partially enclosed to suggest potential divisions of the interior volume and its outfitting. Drawing Credit: François Lévy.