IAC-19,A1,7,x52328

Water Walls 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 failure-prone existing life support systems. The primary innovation is to achieve reliability through the massive redundancy of inexpensive, passive forward osmosis membrane placed within simple but sturdy polyethylene bags. The advantage of using algae for photosynthesis in ECLSS for CO2 removal and O2 production is that it requires an order of magnitude LESS energy than electromechanical methods for physical/chemical systems. This overview begins with an account of the initial Functional Flow concept in revised and simplified form. 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 subsystem level.

Keywords: osmotic membrane, environmental control and life support system (ECLSS), algae, CO_2 sequestration, O_2 production, space habitat.

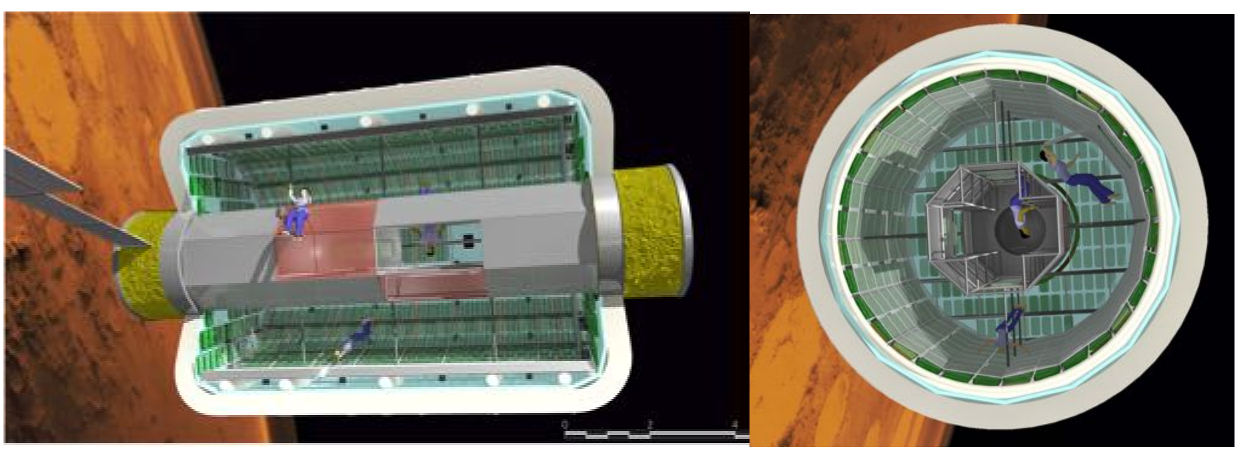

FIGURE 1. Longitudinal and transverse section views of a "TransHab" type space habitat inflatable module showing the Water Walls ECLSS system lining its inner Walls. Credit: François Levy.

Nomenclature/Abbreviations

ECLSS	=	Environmental Control and Life Support System
FO	=	Forward Osmosis
RO	=	Reverse Osmosis
WW	=	Water Walls

1. Introduction

This paper constitutes a condensation of Cohen et al (2012, 2013, 2014), publications that trace the development arc of their Water Walls (WW) concept.[1] It also introduces the authors' critique of the WW approach. WW presents an alternative approach to designing, building, operating, and replacing life support systems for long duration spacecraft. What is most important is that this overview presents for the first time the underlying premise of WW: ***the equations governing photosynthesis in algae — in comparison to the Sabatier process — demonstrate that Sabatier requires an order of magnitude greater energy than photosynthesis to remove CO_2 and to produce O_2.*** Another important new section, Critique of Water Walls, reflects upon the challenges that confront any effort to develop WW further up the Technology Readiness Scale.

Currently, WW is at an early stage of concept development when the challenge is translating laboratory experiments into a functional system. FIGURE 1 shows an early architectural concept for installing the Water Walls system in a space habitat. When fully developed, WW promises to provide nearly the complete suite of functions as the current electromechanical environmental control life support systems (ECLSS), but with higher efficiency, reliability, redundancy, and the additional benefits of growing nutrients and providing radiation shielding. WW aspires to this goal by applying passive membranes that replicate the way living organisms function within 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. Forward osmosis is the process of water diffusion across a semi-permeable membrane in response to a difference in solute concentrations (i.e. osmotic pressures) on either side of the semi-permeable membrane. Because it is passive, it involves less complexity, fewer parts, and less risk from mechanical failure than conventional electromechanical ECLSS hardware.

The key component that makes WW possible in the lab is the FO *bag* -- an inexpensive polyethylene envelope with one or more FO membranes in it. The thrust of the WW project is to develop more FO, 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 within the laboratory context, 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.

Principles of Water Walls

1. Integrate climate control, contaminant control, life support, radiation protection, and thermal systems in a passive system.
2. Achieve reliability through massive redundancy regenerative biological systems.
3. Use primarily passive systems as in nature.
4. Reduce and supplement the use of failure-prone electromechanical and mechanical/chemical systems to functions they do better than passive systems.
5. Provide 100% reuse of all metabolic wastes.
6. Provide radiation protection from metabolic wastes and water; allow no "parasitic mass" for shielding.
7. Provide life support and thermal capability from radiation shield mass allocation.
8. Reduce the cost of human exploration missions by reducing the logistics mass required.

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 (CO2 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.*** . . . 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 [Emphasis added].

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 micro-g 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 osmotic membranes that attempt to replicate the much more reliable and robust processes in nature.

1.1 Goals

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.

The ***Short-Term goal*** is to devise a functional and physical architecture that provides an integrated framework to support the passive water walls ecosystem. The initial concept used soft polyethylene bags with internal membranes for experiments and so projected a complete system using these disposable bags. As of this writing, the WW team is designing a new hardware approach using hard plastic and glass to replace the polyethylene.

1.2 Fundamentals: Photosynthesis versus Electromechanical Systems

The comparison of photosynthesis to electromechanical methods of oxygen production is the starting point to explain the potential advantages of Water Walls' use of photosynthesis compared to the conventional electromechanical life support systems described by the NRC above as inadequate for long duration missions. For application on spacecraft photosynthesis offers a great advantage: far greater efficiency in the consumption of electrical power and zero waste by-products. The best known of the electromechanical processes is the Sabatier Reaction that appears in all the NASA Mars Design Reference Missions (Hoffman and Kaplan, 1997; Drake, 1998; Drake, 2009) and other such concepts, including the MarsOne interplanetary vehicle (Do, 2014), and the Inspiration Mars flyby (MacCallum, undated; Tito, 2013). We compare Sabatier to Photosynthesis as follows:

In the Sabatier Reaction, to crack O_2 from CO_2 requires the addition of energy as heat and pressure, plus hydrogen to draw the carbon from the CO_2 into forming CH_4 (methane). This methane becomes a waste product, although it may be collected for a methane thruster on a spacecraft, but would not have such a use on a surface habitat. EQUATION 1 shows the basic Sabatier reaction.[2]

$$CO_2\,(\mathrm{g}) + 2OH_2(\mathrm{g}) \rightleftharpoons \frac{+318.6\ \mathrm{kJ/mol}}{\Delta\, Heat} \rightleftharpoons CH_4\,(\mathrm{g}) + O_2\,(\mathrm{g})$$

EQUATION 1: Sabatier.

In the photosynthesis equation, the chlorophyll liberates O_2 from H_2O, ***NOT*** from CO_2, as in the Sabatier reaction. (EQUATION 2). This distinction is very important because many ECLSS, engineers, managers, and scientists still regard bioregenerative life support through the lens of the Sabatier reactor, and so assume it produces CH4 as a necessary by-product like the Sabatier..

$$6CO_2 + 6H_2O \frac{+199\ \mathrm{kJ/mol}}{Light\ \ \lambda{=}600\ nm} \succ C_6H_{12}O_6 + 6O_2$$

EQUATION 2: Photosynthesis[3]

In photosynthesis, the CO_2 goes completely into making glucose. The H_2 from the H_2O also goes into glucose, that the plants then begin converting to complex carbohydrates and protein. Photosynthesis uses 199 kJ of light energy at the mid-optimal range wavelength λ = 600 nm to liberate $6O_2$. The P/C Sabatier Reaction uses 318.6 kJ to liberate one O_2. Equation 3 shows the difference in efficiency between photosynthesis and Sabatier.

$$6 * 318.6\frac{kj}{mol} = 1911.6\frac{kj}{mol}; so\ \frac{1911.6\ kJ}{199\ kJ} = 9.606$$

EQUATION 3. Sabatier/Photosynthesis energy.

∴Therefore, Equation 3 shows that the photosynthesis equation is almost 10 times more efficient than the Sabatier Reaction in energy required to produce the same quantity of oxygen, but without methanogenic loss of CH_4 from the ecosystem.

2. The Water Walls Concept

The WW central concept is to use passive membrane processes to replicate the natural processes that define the biological world. The WW concept presented here derives from several approaches or perspectives on the challenge of highly reliable life support using passive systems. Within the constraints of *Gödel's Incompleteness Theorems,* the combination of these system approaches emphasized completeness over consistency.

2.1 WW Module Assembly

The theoretical WW module assembly appears in FIGURE 2. The intention 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.

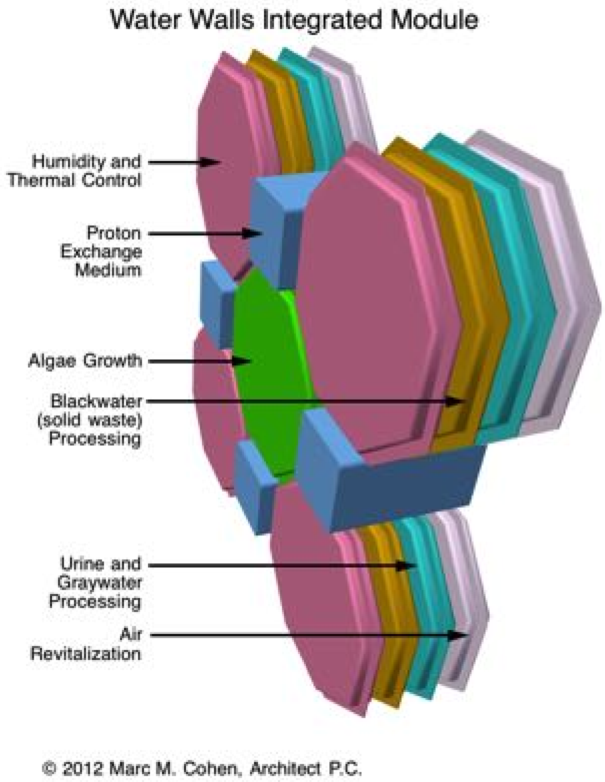

FIGURE 2. Water Walls Multi-Cell Module.
Credit: Marc M. Cohen.

A key objective 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 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. FIGURE 2 shows an example of such a ratio of process units.

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 WW team used simple rectangles for a generic FO bag geometry.

2.2 Functional Flow Architecture

The next step was to design the functional flow pattern that would provide the operational matrix for the WW module assembly and then design the functional relationships and process flows among the FO bags and PEM cells. The significance was that the FIGURE 2 *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 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.

TABLE 1 presents the functions that would occur within WW units. These functions appear across the top horizontal row of column headers. The left column shows the processes that intersect those functions and make them possible. For example, the fifth and eighth rows display the cross-cutting scope of the "nitrogen economy," highlighting how nitrification or denitrification occurs in all five of the critical functions within WW. These nitrogen compounds play a role in determining mass balance and mass-balance flows. 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.

2.3 The Hierarchy of System Integration

The TABLE 1 matrix, with its focus upon the processes within the WW subsystems, leads to an examination of the processes themselves. This examination portrays the WW system as a pyramid made up of horizontal layers. FIGURE 3. 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 would make up each process block; the component level bags, tubing, valves, pumps and sensors make up the subsystems.

2.4 Functions and Their Processes

TABLE 1 displays a first order cross-correlation between the key functions that interact with the nitrogen cycle and the specific processes within that cycle. When trying to process waste — urine, graywater, and blackwater fecal solids — this series of transformations affects all the nitrogenous compounds. The sequence of the nitrogen cycle defines the critical path from biological wastes to fertilizer to growing biomass, carbohydrate, and nutrition.

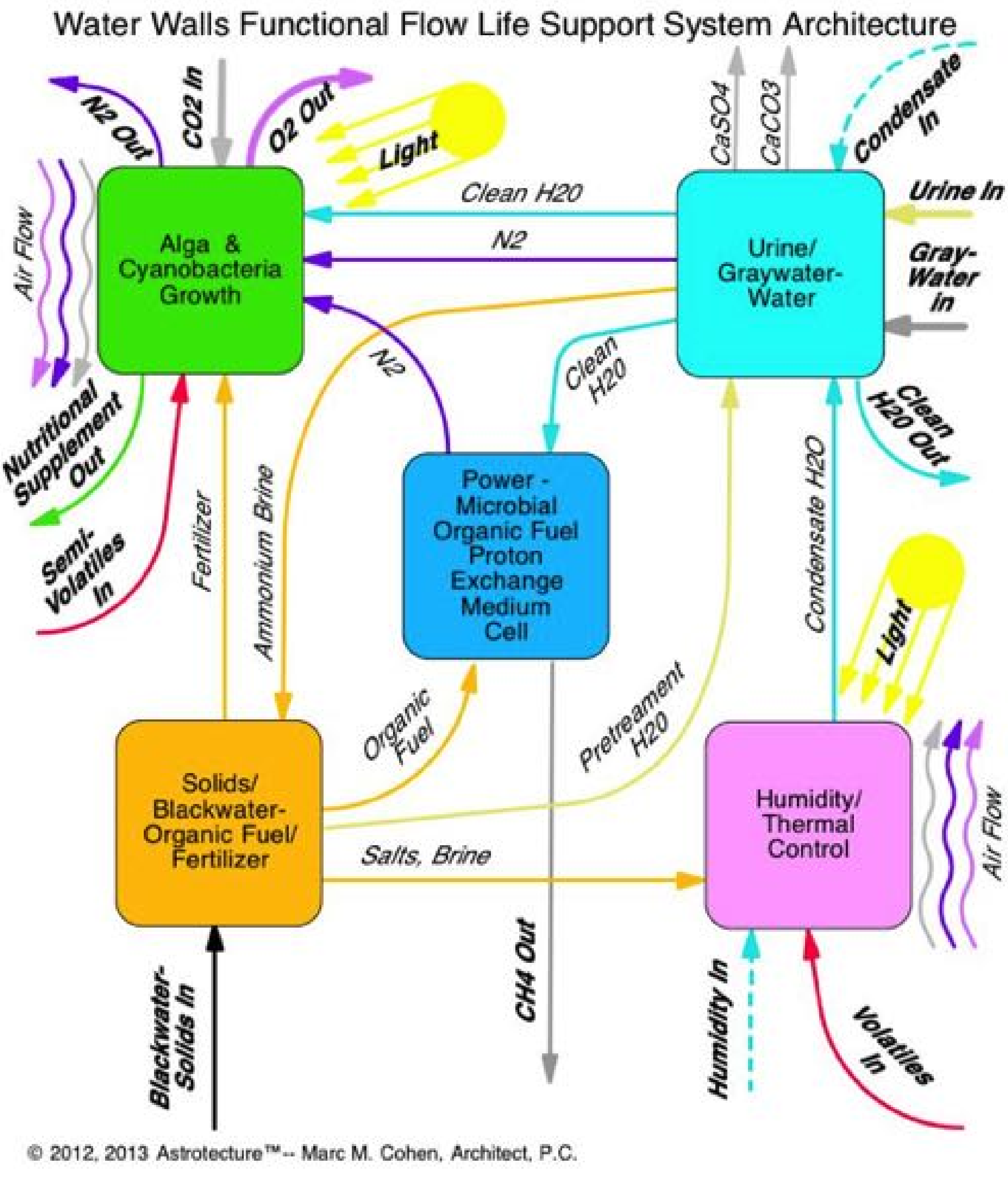

FIGURE 3. The Water Walls Functional Flow Diagram.

TABLE 1. Matrix of Water Walls Functions and the Nitrogen Cycle-Related Processes they Perform.

WATER WALLS FUNCTIONS >> / ∨ NITROGEN CYCLE PROCESSES ∨	Latent Heat Control	Algae Growth	Blackwater / Solids Treatment	Organic Fuel Cell Waste to Power	Urine to H_2O
Blackwater Processing					
Brines Use and Recovery					
Clean Water Production					
CO_2 Removal and Sequestration					
Denitrification/ Liberation of N_2					
Electrical Power Production					
Humidity Removal					
Nitrification and Uptake of Salts					
Nutritional Supplement					
O_2 Revitalization					
Urine/Graywater Processing					

TABLE 1 shows the relationships between key WW functions across the top column headings and the nitrogen cycle-related processes in the left column. The solid-colored blocks indicate the intersections between function and process. The intersection blocks in each column are the same color to emphasize the complexity of these intersections and the recapitulation of the processes from one function to another and how multiple processes occur to make each function possible.

3 The Process Block Construct

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 functional flow diagram in FIGURE 4.

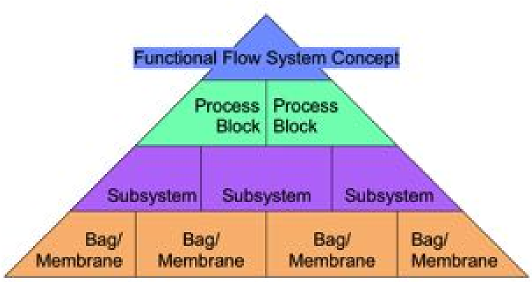

FIGURE 3. Water Walls System Integration Pyramid.

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 three process blocks:

Block 1. Climate Control,
Block 2. Air Revitalization, and
Block 3. Power and Waste
Block 4. Reserved for future higher order plants.

These Process Blocks each consist of several subsystems. Combining of these subsystems and their processes into blocks allows the consolidation of many of their common inputs and outputs. FIGURE 4 shows the initial Process Block Diagram configuration with the four Blocks and the mass flow connections among them.

Contaminant control is an issue for any life support system. The three main contaminants in a spacecraft 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. SVOCs and VOCs persist as a challenge however. 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. The process block approach assigns SVOC destruction to Block 1 climate control and SVOC destruction to Block 2 Air Revitalization.

3.4 The Climate Control Block 1

In FIGURE 4, **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. **Block 1** requires the input of airflow, light, humidity, salts, CO_2 and H_2O. Its inputs include condensate water, O_2, and CH_4. Its outputs include O_2, N_2, and $CaCO_3$, (calcium carbonate), and waste heat. 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. Volatile organic carbon (VOC) refers to all organic carbon compounds that are not part of colloidal or gross particulate matter. VOC Destruction consists of TiO_2-duped substrate exposed to UV light. More complex VOCs will require further analysis for these methods of destruction. The outputs include O_2, N_2, and $CaCO_3$, calcium carbonate.

3.5 Air Revitalization Block 2

Block 2 removes CO_2 from the cabin atmosphere and sequesters the carbon in the tissue of the algae and cyanobacteria, becoming part of the food chain, via photosynthesis. The algae and cyanobacteria sequester the organic carbon from CO_2, and release O_2 from H_2O, which returns to the cabin atmosphere, while the O_2 from the CO_2 becomes part of a glucose molecule. The algae and cyanobacteria can produce foodstuffs, called "nutritional supplement" in NASAspeak. An additional challenge for long duration missions is to process this carbohydrate and protein to make food that is healthy, nutritious, and acceptable to the crew, who may need to eat it for months or years. Block 2 performs Semi-volatile organic carbon (SVOC) destruction. SVOC destruction is intrinsic to the algae/cyanobacteria. However, the SVOC destruction is much more effective when heterotrophic bacteria are mixed with the algae. The investigation of SVOC destruction must focus on what mixture of algae and heterotropic bacteria species proves best suited to this task. The inputs to Block 2 include N_2, CO_2, H_2O, and light. An additional input may be fertilizer from Process Block 3 to Block 2 in the form of NO_3—, NH_4+, and NO_3. Outputs from Block 2 include O_2, N_2, and H_2O.

3.3 Power and Waste Block 3

Block 3, Power and Waste, processes the urine/graywater and solid waste/blackwater while resupplying the Climate Control Block with re-constituted salts and salt brine. Block 3 provides reclaimed water to be reconditioned, polished, and returned to the habitation systems. **Block 3's** organic fuel cells also power to run the basic valves, fans, and sensors imbedded in the WW system. The subsystems within **Process Block 3** are the most tightly bound together in terms of the functional flows among them. The Blackwater and Solid Waste unit produces partially treated waste that flows to the Microbial Fuel Cell to be consumed as fuel. In an analogous way, the Urine and Graywater processing subsystem passes ammonium brine (NH_4Cl) to the Blackwater and Solids unit. The Urine Graywater unit provides clean H_2O to the Microbial Fuel Cell while the Blackwater Solids unit sends secondary or tertiary treated H_2O to the Urine Graywater bag. These **Block 3** subsystems will develop as the most complex biologically, electrically, chemically, and mechanically. The inputs to **Block 3** include condensate, urine, graywater, and blackwater/solids. The outputs include clean drinking water, N2, gypsum ($CaSO_4$), calcium carbonate ($CaCO_3$), nitrate fertilizer, and methane (CH_4).

5. Subsystem Concepts

The subsystems make up the Process Blocks. This section describes the key features 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 FIGURE 4. FIGURE 5 shows the subsystem level in the WW Integration Pyramid.

5.1 Process Block 1 Subsystems

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 would control humidity directly and temperature indirectly. The 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 for each form of heat.

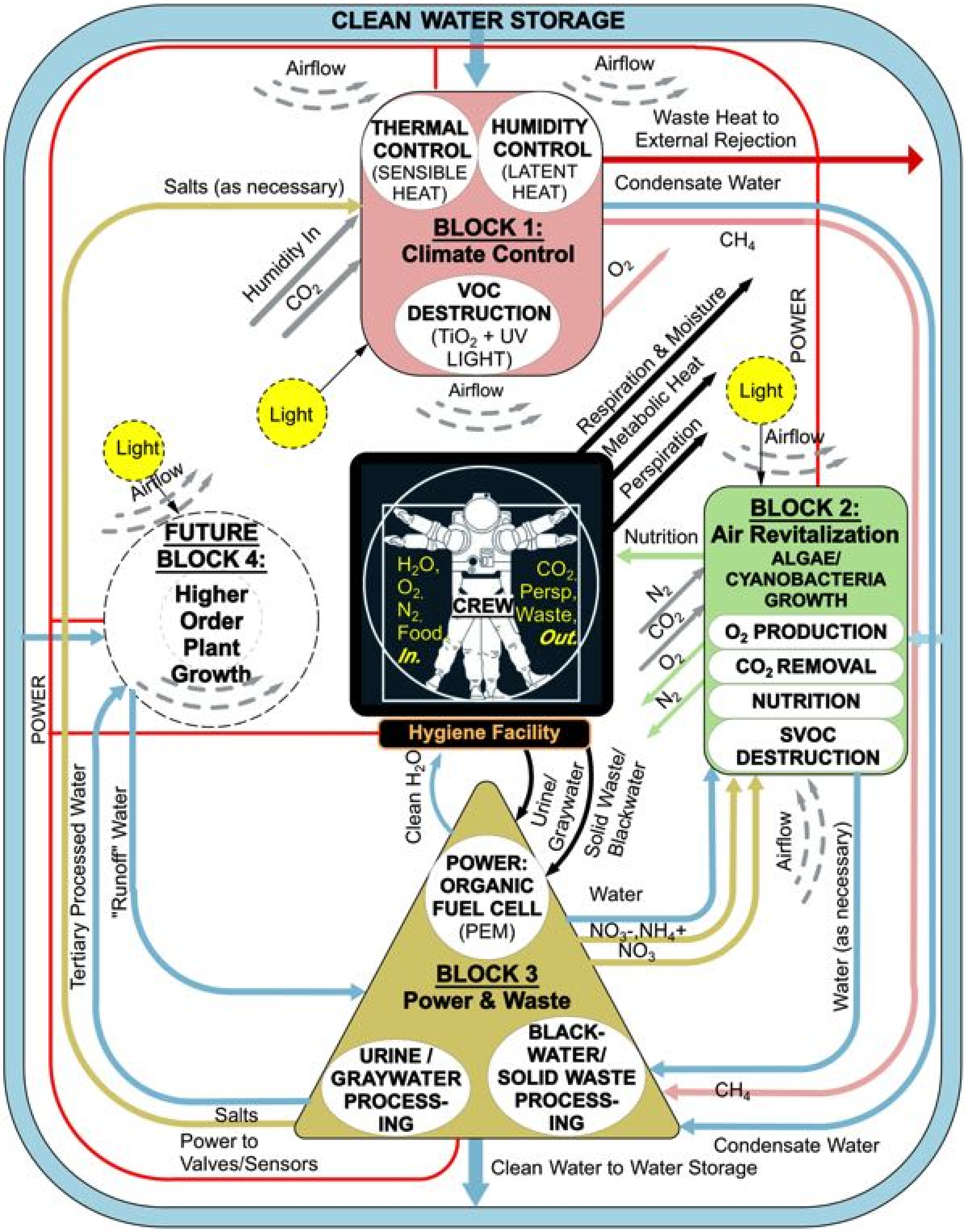

FIGURE 5. Process Block Diagram shows the three fundamental process blocks and the placeholder in Block 4 for future higher order plants for food crops. Credit: Renée L. Matossian, Marc M. Cohen.

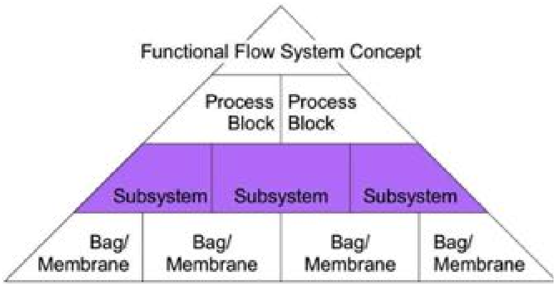

FIGURE 6. Subsystem Level in the Water Walls System Integration Pyramid.

5.1.1 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 would 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 similar to the forward osmosis process used in the Urine/Water Process Subsystem except that it operates with higher salt concentrations, using a gas diffusion membrane as an atmospheric contactor. FIGURE 5 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 then uses a reverse osmosis (RO) pump to remove water from the saline solution resulting in a reconstituted saline solution.

5.1.2 Thermal Control – Sensible Heat

Sensible heat control occurs 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 waste 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.

5.1.3 Volatile Organic Carbon (VOC) Destruction and Removal Subsystem

A vessel element 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. This process is called visible spectrum photo-catalytic oxidation (PCO). PCO stands at Technology PCO's ability to oxidize organics to carbon dioxide and water makes PCO especially attractive for treating spacecraft cabin pollutants. TiO_2 is the most popular photocatalyst employed in PCO due to the hydrophilic properties and its ability to degrade a wide range of inorganic and organic compounds under irradiation of UV or near UV-light. These photo-oxidation and reduction reactions occur simultaneously in the presence of air, so managing a steady airflow over the TiO_2 is important.

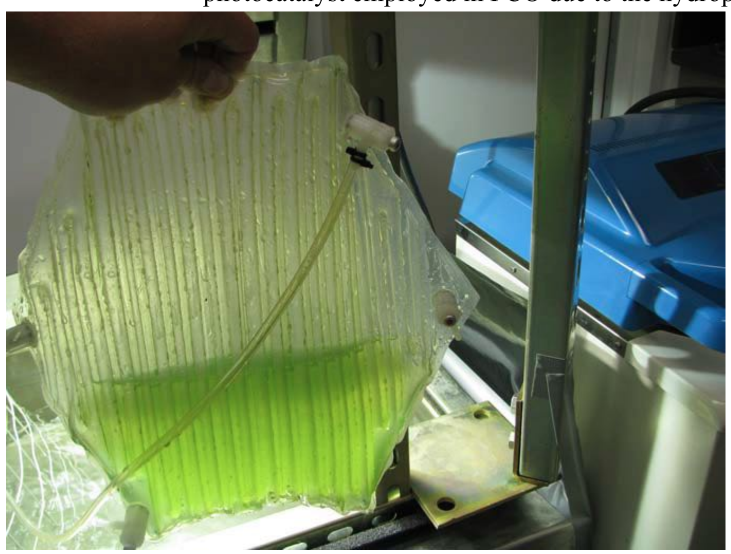

FIGURE 7. Experimental Green Algae Growth FO Bag. NASA photo.

5.2. Process Block 2: Air Revitalization and Algae/Cyanobacteria 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 can occur in one container, the key parameters can behave like four separate subsystems.

5.2.1 Air Revitalization Subsystem

Carbon dioxide removal and oxygen generation occur in the algae vessels. These algal bioreactors will treat all of the CO_2 generated by the crew and other sources. The bioreactors 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. FIGURE 7 shows an example of an experimental algae growth bag.

Managing algal growth means equally managing algal 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.**

TABLE 2 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 shows the Water Walls laboratory setup to grow algae in the experiment that is the basis for the TABLE 2 results.

5.2.2 SVOC Destruction and Removal Subsystem

Water Walls performs semi-volatile removal and destruction using gas permeable membrane units These units may be either dedicated solely to semi-volatile destruction bags or perform 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 (Equation 4) is:

$$ {yi}/{xi} = {Hi}/{P} \qquad \text{EQUATION 4, Henry's Law.} $$

Where, yi and xi are the component vapor and liquid phase concentrations respectively, Hi is the component 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.

Based on the 2009 ESA results from the Columbus Lab module on ISS, if the condensation of cabin humidity achieves a Henry's law equilibrium, then the Total Organic Carbon (TOC) in the space cabin 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 heterotropic bacteria 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 of each compound will set the rate-limiting step.

5.3 Process Block 3 Waste and Power

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, shown in FIGURE 9. The X-Pack® is a forward osmosis (FO) water treatment bag that can produce clean drinking water from seawater, urine, or other wastewater. The X-Pack® bag incorporates two ports. The **green port** serves two purposes: to receive the osmotic agent that creates the solvent/solute disequilibrium to drive 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 X-Pack bag.

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

In-house testing demonstrated the ability to treat wastewater in an X-Pack® bag with a water recovery ratio of 90%. The testing also measured urine 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.

5.3.1 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 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 sugar afford inexpensive and readily available OAs. As byproducts, this subsystem produces ammonium brine that goes to the blackwater/solid waste processing subsystem within Block 3. The Urine and also creates the byproducts $CaSO_4$ and $CaCO_3$ in small amounts[3], for which the WW system does not have a particular use at this time.

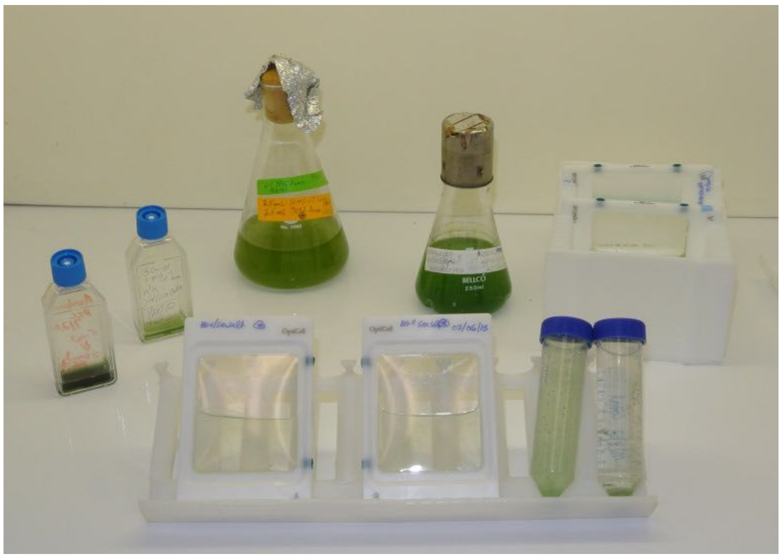

FIGURE 8. Cyanobacteria Baseline: Control Experiment for Cyanobacteria in Rocco Mancinelli's (BAERI) Lab at NASA Ames Research Center (Building N239A, Room 201).

FIGURE 9. Hydration Technologies Inc. Seapack® Desalination Bag. Water Walls uses this general type of bag for experiments. Photo: Marc M. Cohen.

TABLE 2. 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 Thickness	Algae Units at 0.225m x 0.45m Membrane size
Mancinelli	Anabaena	777.3	0.7773	44.00	436
Mancinelli	Synechococcus	166.7	0.1667	9.60	95

5.3.2 Blackwater and Solids Processing Subsystem

Solid waste treatment involves the processing and dewatering of solid wastes through distinct steps. The first step collects the concentrated brines produced from the water treatment. The second step combines these brines with feces and wet trash in a FO bag. The third step adds 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 by venting to the vacuum of space or through a vacuum pump. FIGURE 13, below, illustrates this sequence of steps.

5.3.3 Bioelectrochemical System (BES)

One means to reduce biological wastes is an organic fuel cell, using either chemical or microbial processes. WW contemplates using microbial fuel cells to produce electricity. This power from waste systems can provide localized low power sources for the WW, greatly reducing the need for complicated wiring harnesses and buses to provide power to sensors, valves, and even small pumps. A higher-powered intermittent operation actuator, such as a valve, would be powered by a battery or capacitor that was then recharged. The Water Walls project baselined a Microbial Fuel Cell (MFC) to provide this utility.

6. 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) Control,
FIGURE 11: Air Revitalization Subsystem,
FIGURE 12: Algae Bags in a Habitat Module, and
FIGURE 13: Wastewater Treatment Cycle

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.

6.1 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.

6.2 Air Revitalization Bag Cycle

FIGURE 11 shows the Air Revitalization units that serve the multi-purpose role of sequestering CO_2 and producing O_2, while removing semi-volatile organic compounds (SVOC's) from the cabin atmosphere. The Air Revitalization Bags are primed with freshwater algae, freshwater cyanobacteria, or marine (saltwater) cyanobacteria that incubate in the bag. Resulting population growth fills these bags to capacity. At the end of the life cycle, dead cell mass accumulates in the bags. The system may redistribute remaining mature, healthy cells among new bags to start the next generation of algae/cyanobacteria growth. Dead biomass can then be processed as waste, composted as fertilizer, or pyrolized to carbon.

6.3 Bag Installation at Habitat Module Wall.

FIGURE 12 shows a detail of the Algae Bags installed in a Habitat Module. Bags have input and output ports on both sides, and can be linked in series as necessary. The modular nature of the bags allows for flexible placement within the habitat, but the majority of the bags would be placed at the periphery to provide continuous radiation shielding for the crew.

6.4 Wastewater Bag Cycle

FIGURE 13 shows the Wastewater Treatment Cycle Subsystem. 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 units 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 the Blackwater processing subsystem, where it draws water from biological waste.

7. Architectural Concepts

The architectural success of WW would come 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. This approach requires designing the habitat module from the inside out: the life support system and its architecture comes first.

As in the design of terrestrial buildings architecture serves as the integrative discipline, coordinating all crew, engineering, and operational aspects of the ECLSS into the whole. In Space Architecture, this integration imperative becomes all the more important. Integrating all the human support functions into the spacecraft or habitat from the beginning of the design process substantially reduces development risk and cost, because it avoids needing to make a flood of design changes late in the engineering, manufacturing, and outfitting processes.

FIGURES 14 and 15 present a design conjecture that it would 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 BA330 TransHab*-type module because geometrically it is about the simplest habitat geometry in the literature. However, it may not be reasonable to assume that all space habitats will present such a simple geometry with such a large area of uninterrupted surface on which to install the WW components.

8. Critique of Water Walls

Initially, WW showed great promise and won a NIAC grant and an Ames Center Director's Fund grant. However, the WW team encountered difficulty moving up the concept up the TRL scale and attracting new funding to enable that progress. This section presents a dispassionate critique of the whole WW concept, the claims that its champions made, and the ways that the space life support community perceived the whole approach. WW retains great promise, but until its advocates can recognize and respond to these shortcomings it will remain just that, only a promise. The key challenges and issues for WW include:

8.1 System Functioning

The first issue concerns the failure to distinguish clearly between the functioning of mechanical ECLSS such as the Sabatier reactor and the functioning algae-based photosynthesis atmosphere revitalization system. Although this paper finally presents the equations, WW needs to elucidate the operational difference between the Sabatier's cracking of CO_2 to liberate O_2 and to produce CH_4 as a by-product, and the algae's sequestration of CO_2 as carbohydrate, while liberating O_2 from H_2O.

8.2 Forward Osmosis Bag Suitability

The WW studies to date placed excessive reliance upon the commercial Seapack® desalinization bag to implement all aspects of Water Walls. In fact, this product does not meet some key requirements for the broad range of WW functions. It will be necessary to develop a new FO bag with different inflow and outflow ports, some of which must include flow control valves to prevent reflux.

8.3 Equivalent System Mass (ESM)

WW needs an ESM analysis with corresponding volumetric estimates, to determine how big a WW ECLSS would be and how much it would weigh. A main driver for the volumetric sizing will be the surface area necessary to afford illumination to the algae bags and access to the several other types of process bags or units. With this lighting and all the other necessary infrastructural elements, the total ESM will add up to substantially more than just the FO bags alone.

8.4. Credible CO2 Removal and O2 Production

The WW team overhyped some of the idealized features, and that damaged their credibility in the space ECLSS community. The team was not able to explain the "mechanics" of how some of the WW FO bags operated when presenting them at a conference (Cohen, Flynn, Matossian, 2012). The underlying reason for this deficiency was making certain assumptions without vetting and substantiating them sufficiently. Since that time, the WW team devoted a great deal more attention to the use of algae and cyanobacteria to remove CO_2 from the atmosphere and liberating O_2 into it. This scrutiny led to eliminating a quasi-mystical concept for FO processing for air revitalization and its replacement with a much more extensive use of testable algae/cyanos. This "lesson learned" suggests that all the other WW process blocks, subsystems, FO bags, and other components will demand an equal or greater level of testing to prove their credibility and efficiency.

8.5. Crew Factors and WW Operations

The idea that the crew would move the WW bags filled with blackwater/solids waste arose without any serious consideration of "crew factors" poses a serious shortcoming. First, the WW design engineering must estimate and then determine experimentally how much crew time would be required to maintain and operate the WW system and how often the crew would need to devote attention to it. Second, this research and development needs to consider that more than a "nominal" commitment of time and involvement may trigger a consensus veto from the astronaut crewmembers to the whole WW system. Therefore, a major development task will be to design, build, and test components and subsystems that run almost entirely on their own, without a need for crew intervention or attention beyond routine status monitoring.

8.6 Managing the Osmotic Agent(s)

A key aspect of forward osmosis is that it needs an osmotic agent — typically a salt or a sugar — to induce the fluid of interest to cross the semi-permeable FO membrane. The conventional way to remove the osmotic agent is through reverse osmosis. RO water filtration systems are well developed commercially, and quite inexpensive compared to spaceflight hardware. The issue that arises is what to do with the used RO agent. One possibility to explore is recycling it for reuse in the WW system. Failing a reasonable recycling method, the obligation will be to find a way to dispose of it safely and hopefully in a beneficial way. It is possible that a sugar- or other carbohydrate-based osmotic agent could be recovered through RO and used as fertilizer for algae or plant growth. With a saline osmotic agent, they non-FO reuse opportunities appear to be much more limited.

8.7 Sensor Monitoring

All of the WW project assumed the ability to monitor the processes operating within the WW system and to make adjustments in response to that monitoring data. The first challenge here is what type of sensors to apply to monitor the chemical and physical state of the contents of every type of WW FO bag or other element. The second challenge concerns where to install these sensors. The logical option might appear to be to place them in each bag, but then upon replacing the bags, it would become problematic to dispose of the sensor with it. That would make WW much more expensive. An alternative option would be to mount the sensors somewhere outside the bags. One possible location would be to install the sensors in the piping that connects to the bags to monitor the status of the fluid contents as it flows from the bag. A third option may be to apply spectroscopy to look through the bag to determine the chemical composition of its contents. That might require molding-in an "optical window" in each opposite side to the bag.

This

8.8 Self-Sufficient Power Supply

The original WW concept posited sufficient power generation from the organic waste bioreactor to power the pumps, sensors, valves and any other electrical components integrated with the WW system. The development of microbial fuel cells as electro-biochemical power reactors has been established for over a decade (Jacob-Lopes, Lacerda, Franco, 2008; Logan, Regan, 2006). These cells have been commercialized for the chemical, cosmetics, food processing, and pharmaceutical industries, although all seem to require a net input of electrical power. However, there does not yet appear to be sufficient progress in developing microbial bioreactors or microbial fuel cells to provide the combination of power generation and small size that WW would need. Those modern microbial fuel cells that do provide substantial power appear to do so by acting rather like a conventional fuel cell and "burning" hydrogen (Glas, Drandev, Pupkevich, Karamanev, Sept. 2019. In addition, bioengineering researchers at NASA Ames Research Center experimented with organic waste microbial fuel cells but found the power production results disappointing.

What WW would need in terms of organic bioreactor design for power production is a "clean sheet" start that begins by defining the power requirements and use cycles, with projections of potential "load-shedding" to reduce peak power periods. From this data on the how the WW system would consume power, the next step should be a set of performance specifications for the microbial fuel cell. These specifications would include the types of organic wastes available as fuel and what species of microbes might serve to produce power. The microbial fuel cell will afford a major challenge to system engineering methods, including trade and analysis studies.

8.9 Determine the WW System Timelines

Another dimension of ascertaining WW performance is the fourth dimension: time. The principal temporal metrics include: start-up time, ECLSS anomaly response time, ECLSS anomaly recovery time, and WW components' lifecycle times.

8.9.1 Start-up Time

The WW system lifecycle begins when technicians or the crew prime the FO bags with osmotic agent and inoculate the algae, cyanobacteria, and heterotrophic bacteria bags with "seed cultures" of the organisms that will grow in them. The time it takes for these cultures to grow and thrive to the maturity that allows them to perform their full functions is the *start-up time.* Start-up times will differ among the various WW subsystems, amounting to days, weeks, or perhaps even months—particularly for the still elusive Process Block 4, higher order plants.

Multiple possible start-up scenarios require investigation. For example, under Scenario A, the crew does not launch or depart until the WW subsystems achieve the maturity readiness level. Alternatively, under Scenario B the crew may need to start their mission more quickly, and might not be able to prime, inoculate, and seed the system until after launch or departure. In either scenario, there will be a need for an electromechanical ECLSS system providing physical/chemical life support until WW comes fully online.

A further complication may arise from the differences in operating WW in 1-g before launch from Earth compared to operating WW in micro-g. The FO flight experiment on the last Space Shuttle flight demonstrated that the essential FO process operates successfully in micro-g, but at approximately half the rate of flow across the membrane as in 1-g (Flynn et al, 2011). The implication goes to not only start-up timing, but start-up sizing. If a WW system of x capacity is required to do its job in micro-g, then a pre-launch start-up of only 0.5x may be allowable to avoid producing excess O2, which can cause problems with oxygen toxicity and flammability. Alternatively, if the entire preparation for spacecraft/space habitat departure occurs in space, for example at the Lunar Gateway Station, the sizing issues may not come much into play, but the start-up timing issues would tend to dominate.

8.9.2 WW ECLSS Anomaly Response Time

Anomalies are bound to occur in the operation of any ECLSS system. The leading question concerns how fast the ECLSS can recognize the anomaly and begin responding to it. These anomalies can include: a sudden drop in pressure, a change in gas mixture such as the partial pressure of O_2, an unexpected change in temperature, the introduction of a gas or particulate contaminant, or an equipment failure. Response time includes detecting the anomaly (or "contingency" in *NASAspeak*), analyzing it to find the probable cause, and determining a course of action or solution to correct it. All three steps—detection, analysis, and correction—require extensive instrumentation on the WW system, computational capability to process the data, and programmed algorithms to recommend or take corrective action.

There is an implicit contradiction in this paradigm of the real–time automated diagnostic system applied to WW. The fact is that biological and ecological systems to not respond very quickly to changes in their environment. So, the implication of a WW system responding to a sudden and potentially catastrophic change in the spacecraft cabin atmosphere is not encouraging. Instead, the necessity to maintain a rapid-response capability throughout the mission dictates that the spacecraft needs to incorporate electromechanical systems for conventional physical/chemical ECLSS. P/C ECLSS by its very nature can respond quickly by increasing power, accelerating pumps, opening or closing valves, or shutting down a zone. Insofar as making an analogy to WW, it is not possible to "shut down" a zone of algae respiring through a *Nunc OptiCell-type breathable* membrane surface of a growth bag.

However, this necessity to incorporate P/C into the larger ECLSS picture should not be regarded as a disappointment or a failure. Instead, it creates the opportunity to institute a better risk management and reliability strategy that employs unlike redundancy between p/c and WW systems. In this arrangement, the WW may serve as the ECLSS "workhorse" doing most of the air-revitalization and nearly all of the water processing at much lower cost in energy. Meanwhile, the P/C ECLSS, would stand-by ready to snap into action to counter an alarming trend in the space habitat's ecosystem.

8.9.3 ECLSS Recovery Time

Following close on the preceding section about ECLSS response times, the time needed to affect the recovery of an environmental parameter that goes out of its normal range poses a further test. In some situations, it may be possible to increase CO_2 removal and O_2 production by activating an extra set of air revitalization bags if the anomalous trend is not occurring to quickly. However, in a real emergency, the only option will be to activate the P/C ECLSS that can affect rapid changes in the atmosphere or the H_2O.

8.9.4 WW Components Lifecycle times

The next consideration addresses the useful lifetime of the WW subsystems and components. Remember that the design of the consumable portions of the WW system intentionally plans on the FO bags, algae growth *OptiCell*-type bags, and other such units. It is unlikely that all types of consumable bags will come due for change-over or change-out at the same time, which would be consistent with the WW's gradual preparation, maintenance, and operation philosophy. However, these variations do not change the imperative that all the consumable units will need to be deactivated and eventually removed from their connections to the WW infrastructure.

At some time—perhaps mid-mission if the spacecraft is too small to install a full complement of consumable bags that serve the entire mission—or certainly by the end of the mission, it becomes time to remove the bags. First, there may be advantages to recovering the brine, sugars, or other osmotic agents for reuse. Second, the biomass that remains in the system, either still active or moribund, may offer use as nutrient or fertilizer, respectively. Third, the blackwater/ solid fecal waste may also offer value as fertilizer or fuel for microbial fuel cells. Finally, the polyethylene bags themselves probably become subject to disposal. If it is not feasible to leave these exhausted bag in place within the WW infrastructure, it will be necessary to store them in a safe and sanitary manner until final disposition.

8.10 WW Consumables End of Life Disposition

One of the fundamental premises of WW is to use up the WW FO bags in a planned, predictable, and gradual scheme. However, that premise does not address what to do with the FO bags when they are all finished at the end of a mission or a voyage in space. If the space habitat is intended for single-mission use, then the FO bags might as well crash into the Moon or burn up in the Earth's atmosphere along with the rest of the habitat.

However, if the spacecraft or space habitat is designed to be reusable, then the exhausted FO bags pose a more difficult disposal problem. First, a maintenance and refitting crew will need to remove the used FO bags and perhaps more of the WW system from the spacecraft. Then, they will install the new system. Presumably, permanent piping, pumps, sensors, valves, and wiring will remain, to which they will connect the FO bags and other consumable components. However, the work crew will still need to recycle or discard the exhausted FO bags in some manner. How they might do that and where they might store them until disposition remains an open question.

Regardless of whether the crew disposes of the used WW bags mid-mission, or technicians do it post mission at a space station, the problem remains of how to conduct such disposal, recycling, and perhaps breakdown into their constituent elements and molecules. The fact is that it will be difficult—if not impossible—to empty the polyethylene bags or "clean" them to remove the diverse biological cellular or waste products. So, it will be necessary to treat complete WW bags "as is" for disposal.

Researchers in the space waste processing field have devoted substantial attention and effort to these types of question, although not specifically for polyethylene based FO bags or other WW consumables. The first option developed that may be suitable is *pyrolysis* (using on board the spacecraft to reduce the mass and volume of diverse constituents, while extracting H_2O and inherent gases (Serio et al, 2008). A further refinement to the pyrolysis process would be to apply torrefaction (defined as a "mild pyrolysis") as a preliminary or preparatory step before full pyrolysis to extract carbon compounds that could be used as a plant growth substrate or for other purposes (Serio et al 2014).

Serio et al (2015, p.16) describe the advantages and benefits of the torrefaction-pyrolysis treatment sequence:

> The proposed torrefaction approach will make it technically feasible to process human fecal waste and related cellulosic biomass waste streams and produce additional water and other useful products in space. This will benefit NASA in allowing for volume reduction, solid waste sterilization and stabilization, and water recovery for near term missions. In the case of longer term missions, more severe (pyrolysis) processing in the same or similar equipment would allow for enhanced water and CO2 production, production of fuel gases (CH4, CO, and H2) and multipurpose carbon, along with ISRU. . .
>
> Torrefaction processing is also complementary to the Heat Melt Compactor (HMC) [28] as a biomass pretreatment step and is compatible with the Universal Waste Management System (UWMS) [29] as a post-treatment step, both now under development by NASA.

Kanapathipillai Wignarajah's heat melt compactor at NASA Ames (Serio et al, 2008) may prove ideal for reducing the discarded polyethylene to blocks, bars, or ingots suitable for reuse as new construction material or feedstock eventually to produce new WW bags during spaceflight.

9. Conclusion

Water Walls (WW) offers a radical concept to replace failure-prone mechanical ECLSS equipment with passive membrane technologies to perform most of the environmental control functions in a long-duration crewed spacecraft (ICES 2014-25). This paper presented an overview of the Water Walls system concept. It described briefly the organization and structure of this system. The system comprises three main Process Blocks: Climate Control, Air Revitalization, and Power and Waste. A fourth possible Process Block is held in reserve for higher order plants as part of the ecosystem. Each Process Block consists of several subsystems, which the chapter describes in terms of functionality. Following these descriptions, the chapter provides more detailed insights into the operating concepts for three of the subsystems: Humidity (latent heat) Control, the Algae/Cyanobacteria Cycle, and the Solids/Blackwater Processing Cycle.

The Water Walls Team developed these concepts based on the forward osmosis membrane bags like the X-Pack that they used for laboratory experiments, studies, and tests. This level of conceptualization is sufficient while the proposed system is at a low technology readiness level (TRL). However, it is probably not realistic to envision flying a Water Walls system composed primarily or entirely of these commercial plastic bags. For success at a higher TRL, the Water Walls subsystem components will need to develop custom-designed and engineered container units for each unique process.

These consumable containers would need to consist of truly reusable or recyclable materials. For those units that could not be made recyclable, they would need to consist of durable and reusable hardware, most likely polycarbonate or Pyrex-type glass. It must be easy to clean and reuse these components. These component vessels will continue to incorporate the passive forward osmosis membrane that is at the heart of Water Walls.

At present, the Water Walls concept overall achieved TRL 2, *concept formulation,* with two notable exceptions for thermal control and forward osmosis in microgravity.

All of the subsystems accomplished TRL-1, basic principles observed, and nearly all of them stand at TRL-2 or somewhere between TRL-1 and TRL-2. The thermal control approach of using tubing with circulating water to pass through the forward osmosis bags to cool or heat the contents derives from the liquid cooling garment used in NASA's space suits, so it starts at TRL-3 *proof of concept.* The Urine Processing subsystem is the most advanced, having been tested extensively in the laboratory and produced as a commercial product. What is more, a Water Walls urine (simulant) processing experiment flew on the last Space Shuttle flight, STS-135 in 2011. With this record, the urine processing technology attained TRL-5, *component or subsystem test in a relevant environment.*

The next major step will be to develop a computational model of Water Walls that can simulate its system. This simulation should demonstrate how the system could establish and maintain the mass-balance throughout the system. It will also test the several variables involved in controlling system operations. As a concomitant of this simulation, laboratory experiments will be necessary to validate the simulation results. Finally, the simulation should demonstrate that Water Walls is feasible as a regenerative life support system for crewed spacecraft and space habitats.

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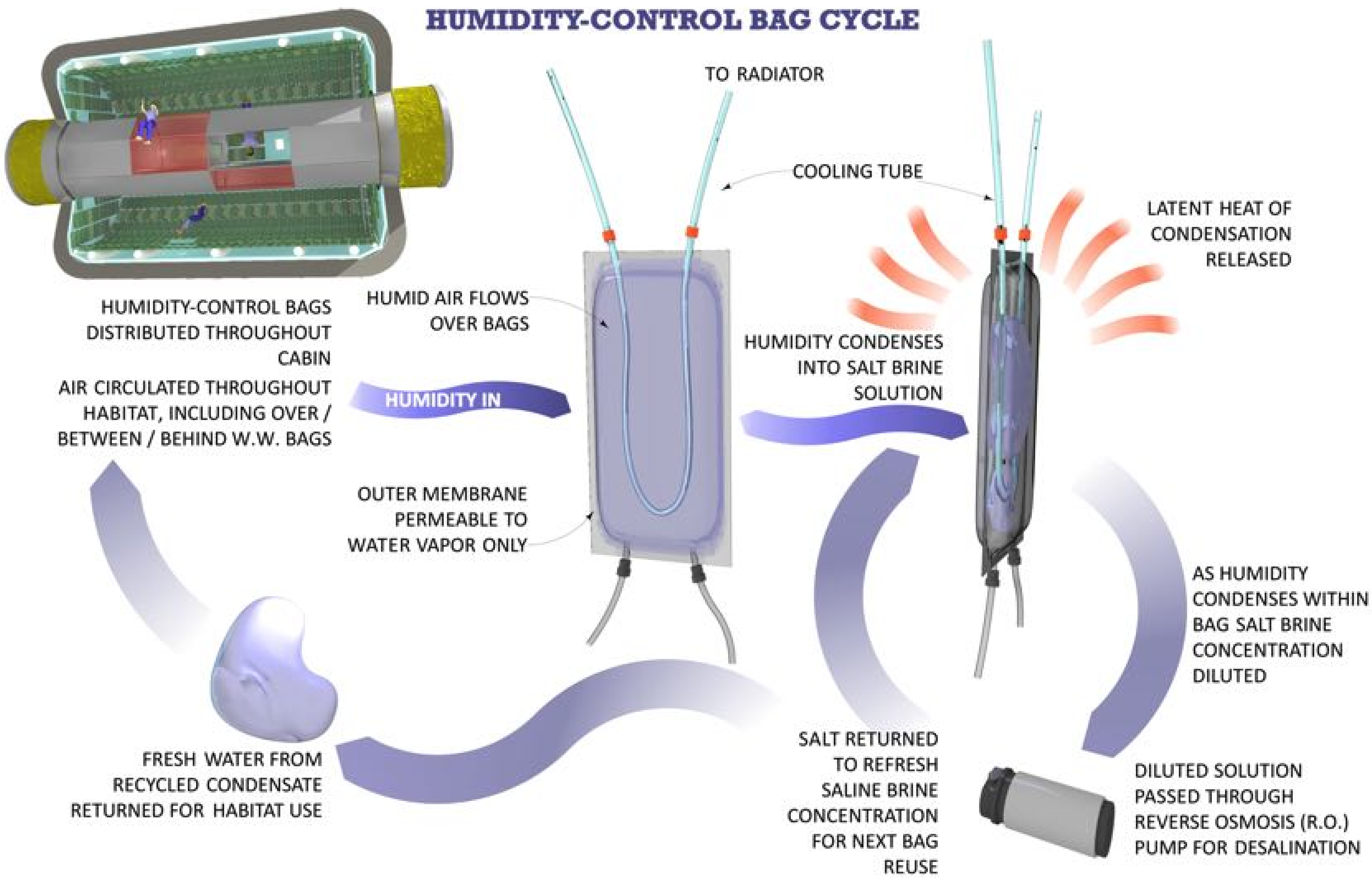

FIGURE 10. Humidity Control Subsystem – Humidity Control Bag Cycle within the Climate Control Process Block. Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

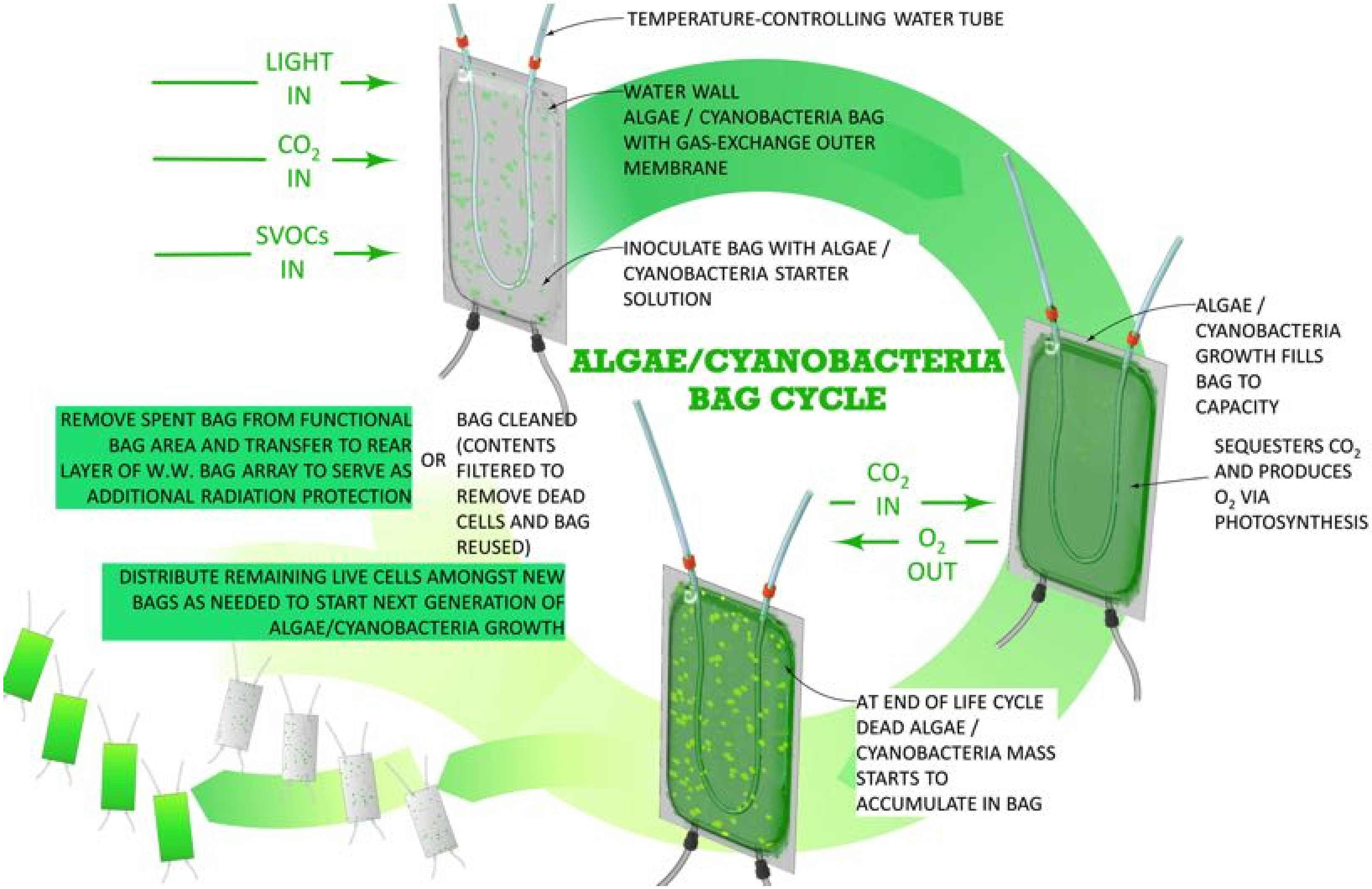

FIGURE 11. Air Revitalization Subsystem -- Algae Growth/Cyanobacteria Growth Cycle.
Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

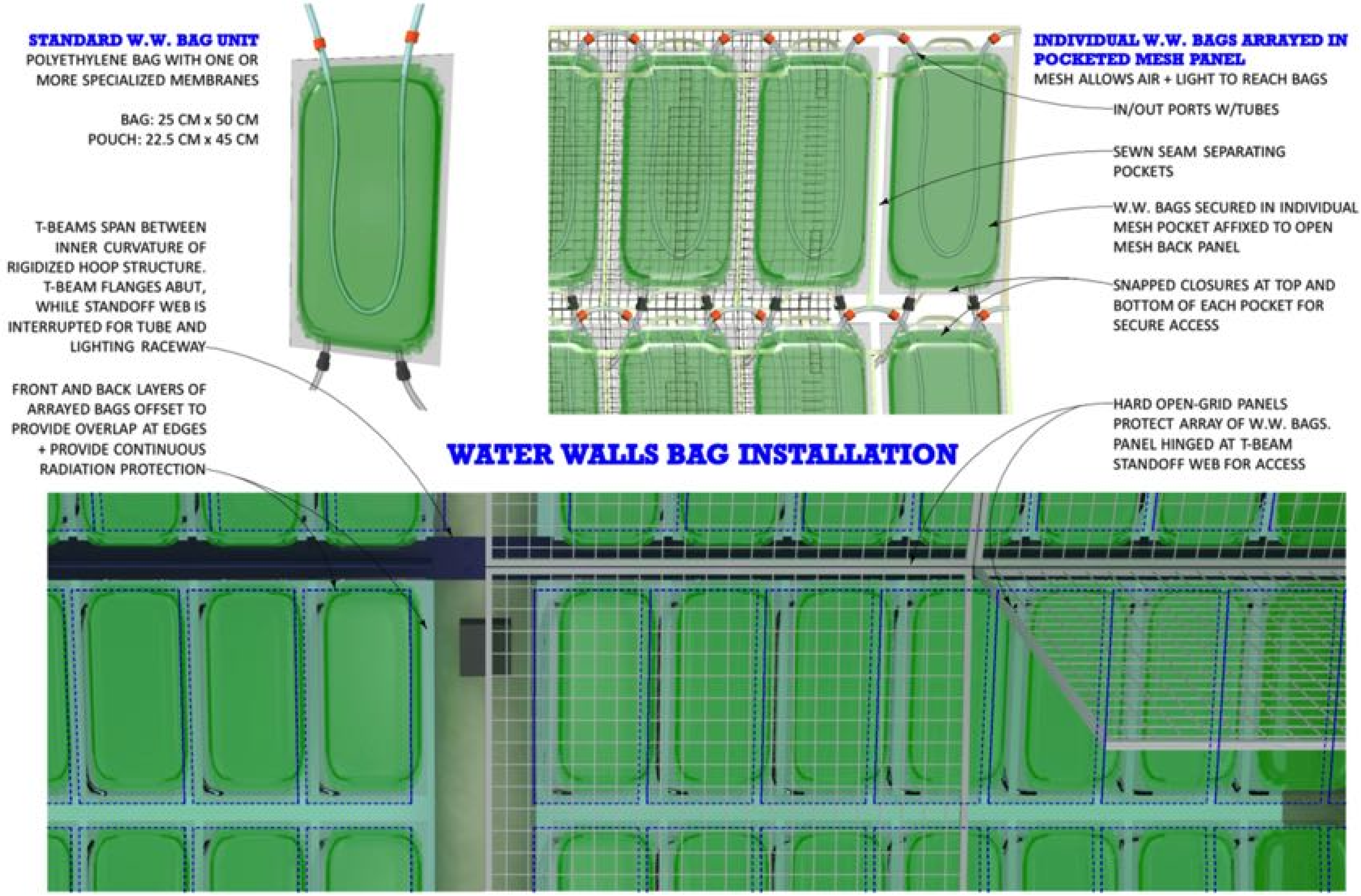

FIGURE 12. Installation of the Air Revitalization / Algae Growth Subsystem in a Habitable Space Module.
Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

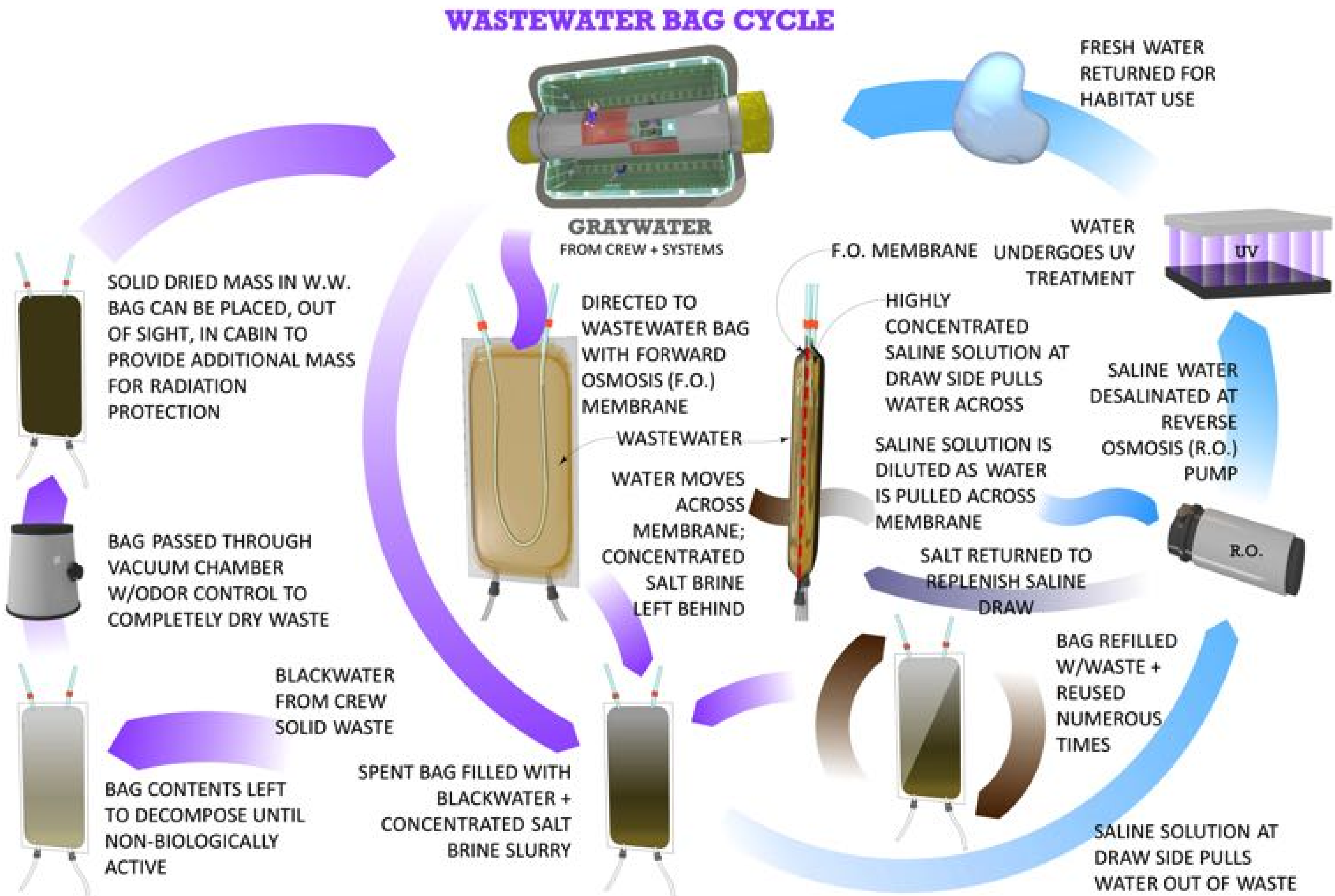

FIGURE 13. Blackwater/Solids Processing Subsystem in the Wastewater Treatment Cycle. Design Credit: Renée L. Matossian. Drawing Credit: François Lévy.

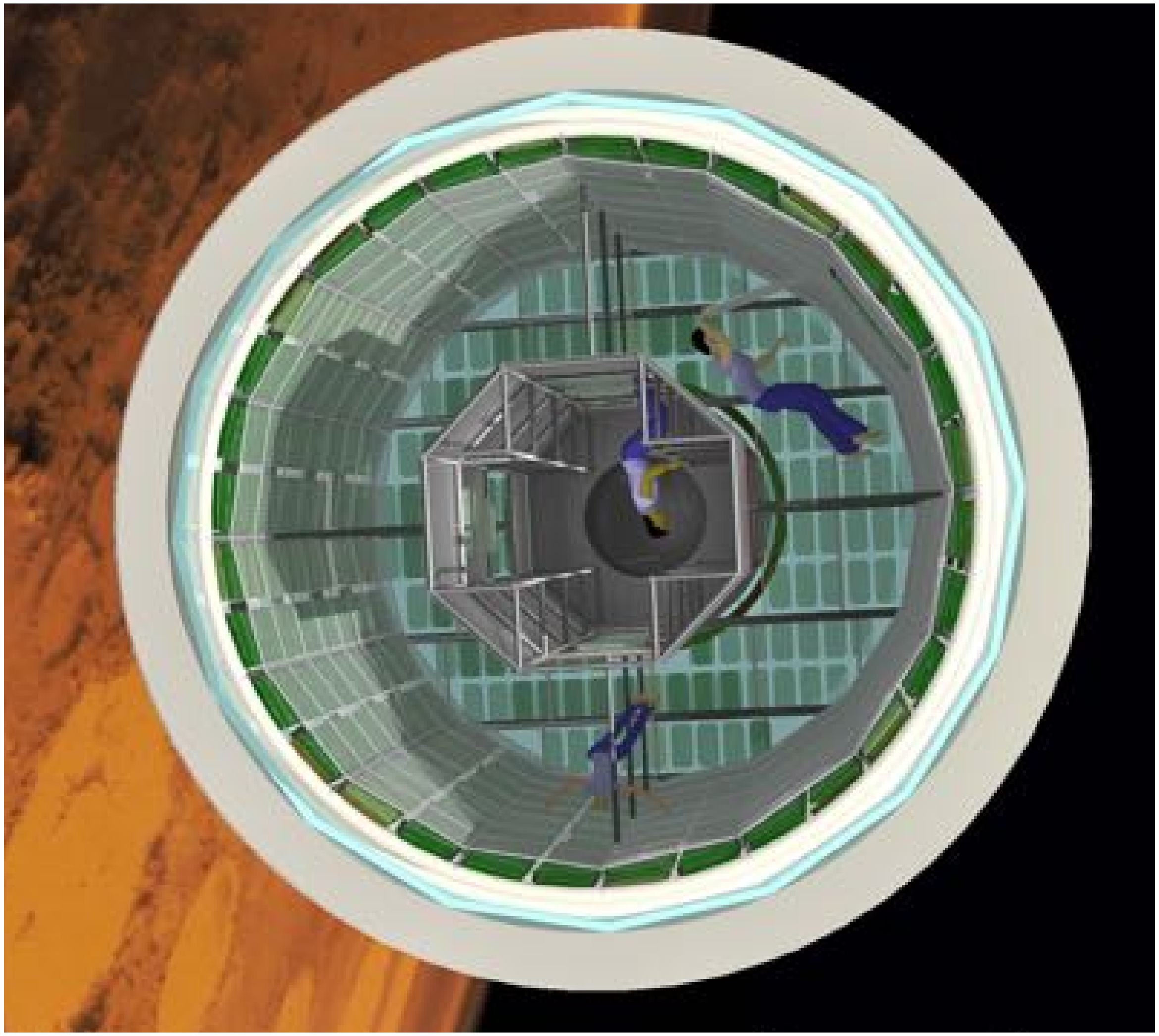

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FIGURE 14. Enlarged view of the transverse section through a Bigelow 330 (TransHab type) space habitat, showing a detailed view of two layers of Air Revitalization Bags installed around the inside perimeter of the cylindrical wall and the flat circular end walls of the inflatable pressure vessel. Drawing Credit: François Lévy.

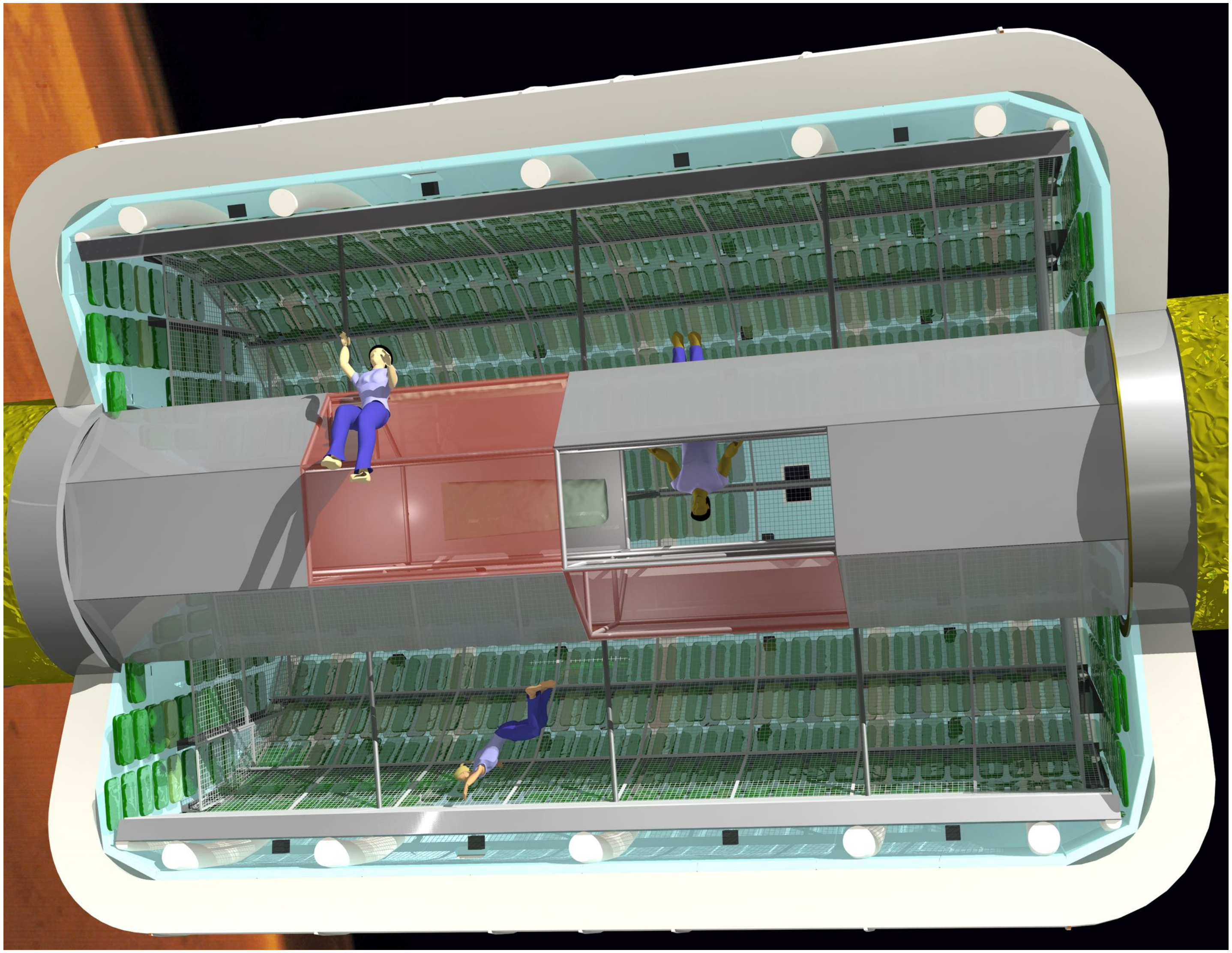

FIGURE 15. Enlarged view of the longitudinal section (from FIG. 1) through a Bigelow 330 (TransHab type) space habitat, showing a detailed view of two layers of Air Revitalization Bags installed around the inside perimeter and end walls of the inflatable pressure vessel. Drawing Credit: François Lévy.

9. Acknowledgements

The authors would like to thank the following colleagues for their contributions, help, participation, and support in the Water Walls NIAC project: Michael Flynn, Sherwin Gormly, Kevin Howard, François Lévy, Renée Matossian, and Jack Miller.

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Endnotes

[1] Michael Flynn, Bioengineering Branch, NASA Ames Research Center was the Principal Investigator for Water Walls under a NASA Innovative and Advanced Concepts (NIAC) Grant and Ames Center Director funding. Besides the authors of this paper, other key participants included François Levy and Renée Matossian.

[2] It is possible to run the Sabatier reaction beyond this basic stage to produce more oxygen, but at a decreased efficiency. This equation does not take into account inefficiencies in converting power to heat and pressure to run the reactor.

[3] The Gibbs Energy (Δ G'°) for the reaction is +114 kcal/mol = 477 kJ. However, it is not straight forward because it is a combination of light and dark reactions. The energy density of glucose is about 17 kJ/kg. The overall photosynthetic efficiency of the system is organism dependent. The cyanos used are ~10-12% efficient using PAR, ~48% of total solar flux. Even at the Δ G'°, the photosynthesis equation is four times more efficient of power consumption than Sabatier.