Water Walls Life Support Architecture

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Water Walls is a concept for a largely passive life support system, centered on the application of forward osmosis membranes to replace the large, complex, and failure-prone machines than now perform these functions. In the present integration, these functions include: Block 1) humidity control, Block 2) volatile organic compound destruction, Block 3) use of algae and cyanobacteria for CO_2 removal, O_2 production, and nutritional supplement, and Block 4) Urine and graywater processing, solids/blackwater treatment, and energy generation. This paper presents the early development work on the Water Walls Life Support Architecture. It describes the initial concepts and shows how the Water Walls team's efforts have matured beyond this baseline.

Nomenclature

CTB	=	*Cargo Transfer Bag*
ECLSS	=	Environmental Control and Life Support System
EELV	=	Evolved Expendable Launch Vehicle
FO	=	Forward Osmosis
IPV	=	Interplanetary Vehicle
ISS	=	International Space Station
LEED	=	Leadership in Energy and Environment
LEO	=	Low Earth Orbit
NASA	=	National Aeronautics and Space Administration
NIAC	=	NASA Innovative and Advanced Concept
OCT	=	Office of the Chief Technologist
PEM	=	Proton Exchange Medium (or Membrane)
PI	=	Principal Investigator
SLS	=	Space Launch System
SMAC	=	Spacecraft Maximum Allowable Concentration
STS	=	Space Transportation System, prefix designation for a Space Shuttle flight.
TRL	=	Technology Readiness Level
WW	=	Water Walls

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I. Introduction

In August 2012, the Water Walls Architecture team won a NASA Innovative and Advanced Concept (NIAC) Award for the Water Walls Life Support project. In addition, Water Walls won a matching grant from the NASA Ames Director's Discretionary Fund. Given that NASA issued the Water Walls subcontract to Astrotecture™ on 1 JAN 2013, this paper reports approximately the first six months of progress under this grant.

Water Walls presents a new and different approach to long duration life support. It investigates using the concepts of synthetic biology and microbiology for the development of bioregenerative life support systems for human space missions. Instead of depending upon a few massive, heavy, extremely complex and expensive, sensitive, and eminently failure-prone pieces of mechanical equipment, the Water Walls approach provides a large number of repetitive, simple units to handle the same functions. Instead of continuously active mechanical systems, Water Walls is almost entirely passive, with only valves and small pumps as active elements – no compressors, evaporators, sublimators, distillers, adsorbers, or desorbers. Instead of all this inelegant crisis/failure mode of mechanical ECLSS equipment, Water Walls units or modules are designed to have their capacity consumed gradually throughout the mission. As one unit is used up, the next in line takes over.

Water Walls (WW) will provide the life support functions of CO_2 removal, O_2 revitalization, urine and gray water recycling, and solid waste processing. The WW basic unit is a polyethylene bag with one or more forward osmosis (FO) or other specialized membranes in it, and valved orifices for input and output. Currently, the WW water processing function is fully mature, with FO bags available commercially. NASA Ames Research Center implemented an FO recycling system for urine and wash water in the new "Sustainability Base" green building. The next step is to complete development and implementation of solid waste processing. Finally, air processing is in basic research for FO bags that will have an active membrane on the exterior of one side and another inside.

WW accomplished two technology readiness milestones in flying an FO bag experiment in a cargo transfer bag (CTB) on STS-135, the last shuttle flight, in July 2011 (Flynn, et al; 2012). First, it achieved TRL-3 proof of concept that the FO processes would operate successfully in microgravity. Second, it achieved TRL-7 spaceflight testing for the specific CTB subsystem. WW presents additional advantages for integrating life support into the architecture of a spacecraft or space habitat. The liquid-filled FO bags can provide a degree of *non-parasitic* radiation shielding (meaning that the requisite shielding mass serves a secondary purpose beyond mere shielding capability). WW can also provide a source of nutritional supplement from harvesting the algae used to help replenish the atmosphere.

II. Approach

This paper presents the baseline concept for Water Walls circa April 2012 and shows how the development concept has evolved over the year. This comparison follows the original structure for the WW investigation. The original design research structure for Water Walls consisted of these specific aims:

1. Module Assembly
2. Functional Flow Architecture
3. Sizing and Modularization
4. Organic Fuel Cell
5. Spacecraft Architecture.

To these sections, the WW team's subsequent work adds:

6. The Nitrogen Economy

A. Module Assembly

The original module assembly concept was to provide the functional adjacency, physical modularization, and structural framework for WW. FIGURE 1 shows an example of that construct. This figure shows the architectural concept for a basic Water Walls Integrated Module that incorporates multiple types of octagonal-shaped FO bags in four layers. The nominal depth of each FO bag is 10cm and the nominal width is 50cm from parallel edge-to-edge. The nominal thickness of water and biomass for radiation shielding is 40cm for an areal density of 40g/cm^2, plus the polyethylene encasements. The proton exchange medium tanks provide the structural matrix to attach and support the FO Bags. Creating this assembly design enables all the subsystem and component development to follow in later phases and under separate funding lines. 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.

What has changed?

The idea of a single module that could integrate or incorporate all the functions of Water Walls into a compact unit is proving so far to be extremely difficult to achieve. This difficulty arises from two causes, the ratio of function cells and the suitability of a single integration and optimization module.

First, the ratio of function-specific cells must vary with the optimization strategy. Optimizing for the algae growth cell will produce a different ratio than optimizing for solid waste processing. The effort to achieve these different combinations is yielding a potentially better basis for integration: the ***Process Blocks*** that appear in FIGURE 3.

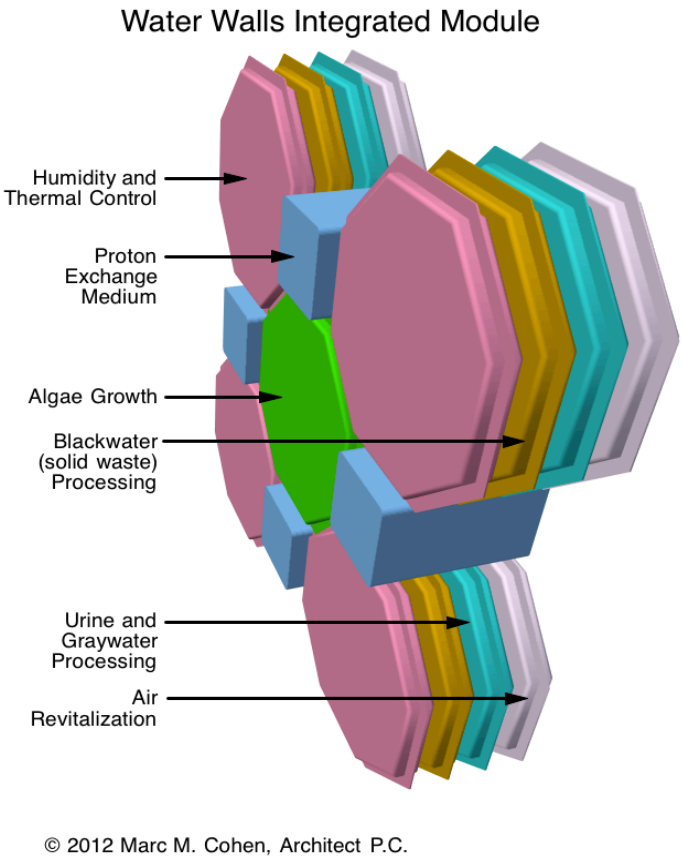

FIGURE 1. Original Water Walls Multi-Cell Module Architectural Concept.

Second, the fundamental idea of putting all the functions into a single, "one-size-fits-all" module may turn out to be mistaken. It may prove more efficient and flexible to create several more diversified modules that can concentrate sub-groups of processes with less complicated cell ratios. Also, by decomposing the original "Water Walls Integrated Module," it could be possible to install each separate combination in different areas or volumes of a space habitat or crew cabin that may serve as the most favorable location or functional adjacency.

B. Functional Flow Architecture

The functional flow diagram is the heart of the system architecture. It postulates 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, showing how the effluent from one FO bag is the feed for another bag or PEM cell; which bags require surface air flow or light, and most important the output consumables (O_2, N_2, water, algae nutritional supplement). The Functional Flow Architecture explicates the functional relationships and process flows among the FO bags and proton exchange membrane (PEM) cells as shown in FIGURE 2.

What has changed?

The challenge of defining the integrated Water Walls modules led initially to the idea of consolidating the functional cells into less complex, less tightly integrated modules. With this insight, the Water Walls team began rethinking the Functional Flow Diagram in FIGURE 2, to create the Process Block construct in FIGURE 3. This framework consists of four Process Blocks, summarized in TABLE 1. A theoretical Block 5 would be reserved for future higher order plants.

TABLE 1. Summary of the Four Water Walls Process Blocks

1. Climate Control. a. Humidity Control (Latent Heat) b. Thermal Control (Sensible Heat)	2. Contaminant Control. a. Volatile Organic Compound Destruction b. Semi-Volatile Compound Destruction
3. Air Revitalization using Algae or Cyanobacteria (Spirulina) Growth for: a. CO_2 Removal b. O_2 Generation c. Nutrition Production	4. Waste and Power: a. Power: Organic Fuel Cell b. Urine & Graywater Processing c. Blackwater/Solids Processing

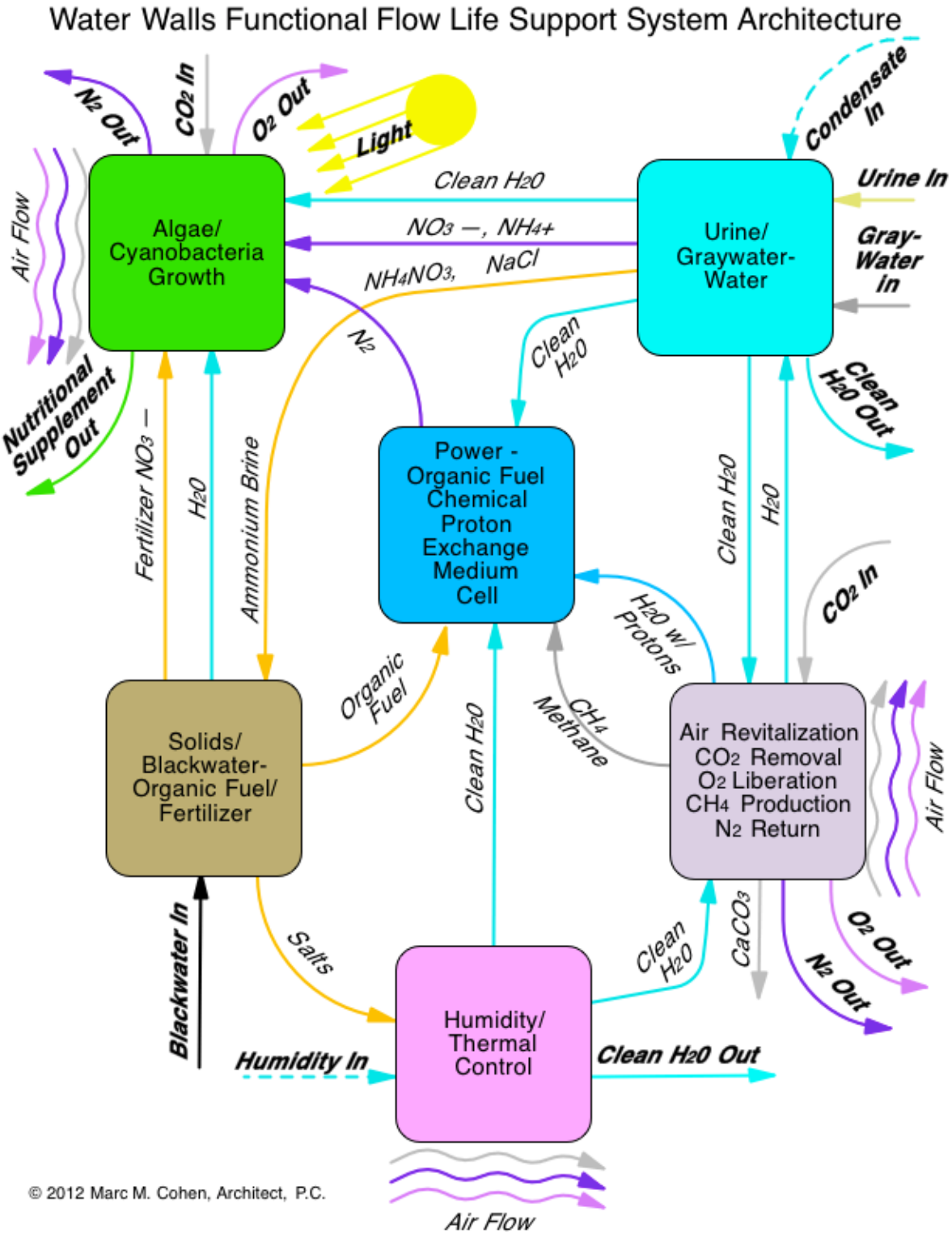

FIGURE 2. Original (revised 15 DEC 2012) Functional Flow Diagram for Water Walls Architecture.

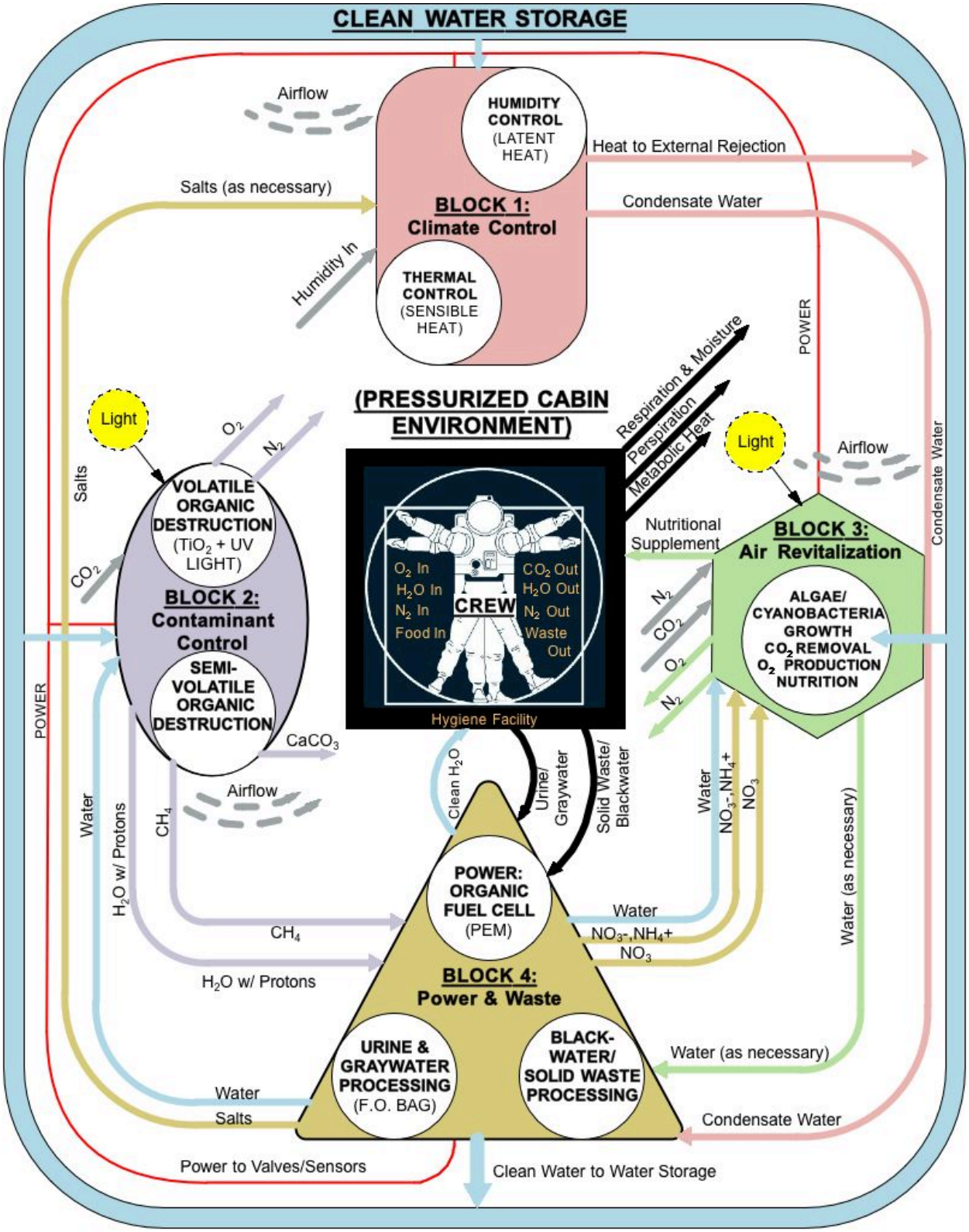

FIGURE 3. Water Walls Process Block Diagram (26 FEB 2013).

The change from the functional flow construct to the process block one derives from early results in determining the technology readiness of each component. The most significant of these determinations concerns the Air Revitalization Block 3 which would have removed CO_2, and cracked it with H_2 generated from water electrolysis, forming CH_4 and O_2.

1. Problems with the Electrolysis Air Revitalization Bag

The goal was to achieve a room temperature, ambient pressure approach using FO as an alternative to a Sabatier reactor. At the time we first proposed Water Walls to NIAC, a year ago, there was ongoing work on this air revitalization approach and we were hopeful that it would provide a true "game-changing" solution. However, this approach encountered substantial issues regarding temperature, pressure, and excess production of O_2 for this largely theoretical membrane bag approach. Therefore, the WW project shifted attention to the alga and cyanobacteria cultures as a more viable approach to provide carbon sequestration and O_2 production for the present grant cycle.

2. Biological Air Revitalization Alternatives

At the same time, we have been finding more and more favorable reports about the use of biological processes with algae and cyanobacteria. Both these phyla use photosynthesis to remove CO_2, fix carbon, and liberate O_2, while producing nutritional biomass. Therefore, we are focusing on algae and cyanobacteria, and not pursuing any work on the electrolysis air revitalization bag approach.

3. Bioregenerative Air Revitalization -- First Results from Cyanobacteria

We are encouraged by our first results with cyanobacteria. The prior, preliminary studies used the scientific literature to set a baseline for the air revitalization processes. However, for the purpose of this project, it is necessary to establish our own baseline for all organisms and processes within the WW system. FIGURE 4 shows the lab setup for the cyanobacteria species *Anabaena PCC 7120* (freshwater) and *Synechococcus HI 1022* (marine).

FIGURE 4. Cyanobacteria Baseline Control Experiment for Cyanobacteria in Rocco Mancinelli's (BAERI) Lab at NASA Ames Research Center (Building N239A, Room 201).

The initial results for carbon fixation are:

Ten mL of mid log-phase cultures of freshwater *Anaebaena* (PCC 7120) and the marine *Synechococcus* (BG04351) were used to inoculate 500 mL Erlenmeyer flasks containing 100 mL of either BG-11 medium (*Anaebaena*) or BG-11 to which 30 g/L of commercial sea salts (Sigma-Aldrich) were added (*Synechococcus*). These flasks were incubated at room temperature (22 ^{o}C) under ambient room fluorescent lights (16 hrs on 8 hrs off) for 7 to 14 days. After incubation the total organic carbon content of each culture was determined by combustion.

The total organic carbon is directly related to the amount of CO_2 fixed, because all of the organic carbon is derived from carbon in CO_2. Samples for combustion were dried overnight at 80 ^{o}C. The dried samples were weighed then heated for three hours at 600 ^{o}C and weighed. The overall rate of CO_2 fixed by *Anaebaena* was 5.36 x 10^{-5} g CO_2 fixed cm^{-2} hr^{-1}. This equals 53.6 mg CO_2 fixed L^{-1} hr^{-1}, very close to the published value of 55 mg fixed L^{-1} hr^{-1} under similar conditions (e.g., Jacob-Lopes et al., 2008, Biochemical Engineering Journal, 40:27-34). The overall rate of CO_2 fixed by the marine *Synechococcus* was greater, equaling 25 x 10^{-5} g CO_2 fixed cm^{-2} hr^{-1}, equaling 250 mg CO_2 fixed L^{-1} hr^{-1}. TABLE 2 presents these carbon sequestration results.

The reasons for the difference in results between the freshwater and marine cyanobacteria are under investigation. TABLE 2 sums up these results. Ongoing tests include conducting similar experiments using species of the green alga *Chlorella*, and the edible cyanobacterium *Spirulina*. The next major step is to examine CO_2 fixation rates in the Water Walls candidate bags.

TABLE 2. Summary of Carbon Sequestration Results

Organism	Mean dry weight prior to combustion (based on 100 mL culture)	Mean wt. after combustion	Amount lost through combustion =g organic-C	CO_2 sequestered (for every mole of C fixed 2 moles of O_2 fixed)
Anabaena	0.157±0.02g	0.056± 0.007g	0.101±0.012 g	0.642± 0.08 g
Synechococcus	0.736±0.09g	0.262± 0.03g	0.474±0.06 g	3.011±0.3 g

C. Sizing and Modularization

TABLES 3a and 3b present the modularization matrix for Water Walls. Specifically, TABLE 3a presents the initial matrix and TABLE 3b presents the current matrix. The main new development with respect to sizing and modularization involves the addition of the line for the Denitrification/Liberation of N_2. These nitrogen-related processes occur in more types of cells or bags than any other process. What is more important, these nitrogen processes add up to the nitrogen economy, which could serve as the algorithm for sizing the number of FO bags of each type.

TABLE 3a. Original Matrix of Water Walls Life Support Functions and Systemic Redundancies

WW Primary Functions (Based on Inputs and Outputs)	Air Bag	Algae Growth Bag	Solids Bag	H_20 Bag	Humidity & Thermal Control Bag
O_2 Revitalization	X	X			
CO_2 Removal	X	X			
Clean Water Production				X	X
Urine & Graywater Processing				X	
Semi-Volatile Removal	X	X			
Blackwater Processing		X	X		
Humidity & Thermal Control					X
Nutritional Supplement		X			

An additional change to TABLE 2b is the deletion of the Water Electrolysis-Air Revitalization bag column. The result of this shift is that now the Algae growth bags are the sole method of oxygen production. A further change is the deletion of thermal control from both the Humidity and Thermal Control row and column. The reason for this change is that while the humidity control approach represented by the JPL-Ames "Air Team," has become much more clear to the WW team, the specific Thermal Control function itself that will be necessary for WW has, if anything, become less clear at this time. A final pair of additions is the Electrical Power Generation row and the PEM Fuel Cell Column.

What is most apparent about this set of revisions is that they now reflect three of the four Process Blocks.

TABLE 3b. Current Matrix of Water Walls Life Support Functions and Systemic Redundancies					
Process Block:	**1. Climate Control**	**3. Air Revitalization**	**4. Power and Waste**		
WW Primary Functions (Based on Inputs and Outputs)	**Humidity Bag**	**Algae Growth Bag**	**Blackwater/ Solids Bag**	**PEM Fuel Cell**	**Urine/ H_20 Bag**
O_2 Revitalization		X			
CO_2 Removal		X			
Denitrification/Liberation of N_2			X	X	X
Clean Water Production	X				X
Urine & Graywater Processing					X
Semi-Volatile Removal		X			
Blackwater Processing			X	X	
Humidity Control	X				
Nutritional Supplement Production		X			
Electrical Power Production				X	

D. Organic Fuel Proton Exchange Medium (PEM) Cell

The Proton Exchange Medium (or Membrane) PEM cell is the only process that rose to the level of a specific aim section in both the original and updated Water Walls concept. The PEM cell occupies this position because of its unique service in providing electrical power to the Water Walls modules to run the associated fans and valves. The original WW concept evoked an organic chemical fuel cell as follows (Cohen, Matossian, Flynn; 2012; p. 10):

> A PEM cell uses organic material, including waste effluent to generate electrical power (Kosek et al, 2009). The specific aim is to design a configuration for the PEM Cell optimized for WW. These systems utilize a two-stage electrochemical approach that first electrolyzes organics and water to produce O_2 and H_2 (Stage 1). The O_2 can supply crew respiration, while the H_2 serves energy production or specialized microbes to convert CO_2 to CH_4 (methane for fuel) using electrical current as their energy source (Stage 2). This approach generates far less residual biomass, and reduces reactor maintenance.

What has changed?

Although the original concept showed a chemical organic fuel PEM, it appears to present problems for the Water Walls application. The chemical PEMs are quite exothermic, so that they tend to run hot, creating a need to cool them. Simultaneously, the WW Principal Investigator, Michael Flynn along with John Hogan, separately won funding under the Synthetic Biology program for new microbial organic fuel cell technology. This shift led the WW team to hold off pursuing the chemical organic fuel cells in favor of this new initiative, which would potentially enable integration into the wastewater process block, but without the cooling problem. John Hogan provided this summary:

Synthetic Biology and Microbial Fuel Cells: Towards Self-Sustaining Life Support Systems
Principal Investigators: John Hogan, and Michael Flynn

NASA ARC and the J. Craig Venter Institute (JCVI) are collaborating to investigate the development of advanced Bio-Electrochemical Systems (BESs) for human life support in space. BESs utilize specifically-adapted microorganisms that can either generate electrical power during the metabolism of substrates (Microbial Fuel Cell - MFC), or can conversely utilize electrical current to "drive" microbial metabolism for the production of products (Reverse MFC). BESs possess numerous advantages for space missions, including rapid processing, reduced biomass formation, and energy efficiency. Additionally, the use of advanced Synthetic Biology techniques offers the potential to genetically modify microorganisms to further increase system capability and performance.

The initial goal of this work was to examine technology infusion of BESs for wastewater treatment and other human

life support functions. Tasks included:

- Identification of potential integration scenarios that use BESs to treat space-based wastewaters
- Investigation of appropriate synthetic biology research and development areas that advance the use of BESs for space
- Investigation of potential power production efficiency and utilization strategies to determine power offsets and power "self-sustainability"
- Investigation of BESs as a means to use electrical power to perform biological processing

Microbial electrochemical cell systems could revolutionize the use of biology to perform various functions. Whereas traditional systems rely upon the supply of complex substrates to organisms for desired product formation, electrochemical systems operate on electrical current. Using *Synthetic Biology*, highly adapted organisms can be engineered to produce electricity or convert CO_2 to mission relevant products (such as CH_4 for fuel use), without accumulating excessive biomass. This strategy provides a sustainable, flexible platform for life support loop closure, and highly decouples the processor from re-supply.

E. Space Cabin Architecture

The benefit of Water Walls is to support a crewed spacecraft for a long duration mission (e.g. asteroid or Mars). To optimally implement that approach, it becomes necessary to design a spacecraft *around* the WW architecture. This imperative demands and enables space architects to design the spacecraft "from the inside-out." For the first time, it becomes feasible to optimize the life support, habitability, and crew productivity – in one unified system for design, engineering, and operations. The WW original proposal stated:

> This application of WW is the first operational solution for "non-parasitic radiation shielding." The spacecraft architecture would install the WW matrix to provide shielding around the crew cabin. It also offers new potential ways to design ventilation and airflow, lighting, and partition walls. The green WW algae bags offer a new way to give color to interior surfaces without needing to certify new paints to conform to Spacecraft Maximum Allowable Concentration (SMAC) levels. On the other hand, the brown solids and yellow urine bags do not offer such an attractive option, so unlike the algae and thermal-humidity control or air revitalization bags, they do not appear on the inward-facing (crew cabin) surface of the WW assembly.

The initial key design construct for cabin architecture grew from the geometry of the pressurized crew module. FIGURE 5 shows an original example of a curvature created among three Water Walls modules. The advent of the Process Block construct means that there may be several types or patterns of tessellation among WW cells or FO bags. FIGURE 6 shows a linear array of WW modules that can be paneled around the inside of a cylindrical module.

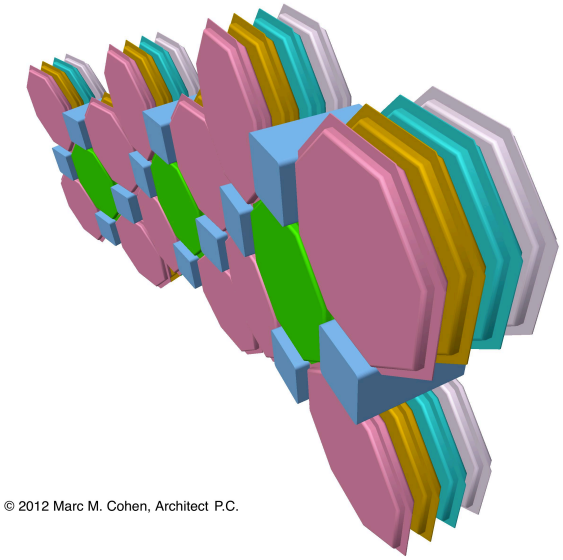

FIGURE 5. Tessellation of the Water Walls Modules to form a curved surface.

Future Considerations:

Water Walls architectural concepts will need to accommodate the following sets of variables:

1. The different modules that implement each of the new Process Blocks.
2. The variations in the shape, proportions and construction interface of the pressure vessels in which to install the WW modules.
3. Variations based on size of crew, mission duration and type of mission (LEO vs. deep space).
4. Providing full accessibility to individual modules to allow for bag installation, maintenance, replacement and reconfiguration.
5. Accommodating system upgrades and changes in technology.

Perhaps the greatest change will occur as the team members design WW modules for different sections of a space habitat or crew cabin. For example, it may prove most efficient to implement a set of Block 4 Power and Waste modules. In that case, the most effective adjacency relationship will be to place it in close proximity to the hygiene facility that would be the origin of the liquid and solid wastes that provide the fuels for the PEM cells and also the urine and graywater for the FO water purification bags. The Climate Control Block 1 and Contaminant Control Block 2 may serve best being evenly distributed throughout the cabin. The placement of the Air Revitalization Block 3 will depend – at least in part – upon proximity to the ambient lighting sources and their view angle toward those lights.

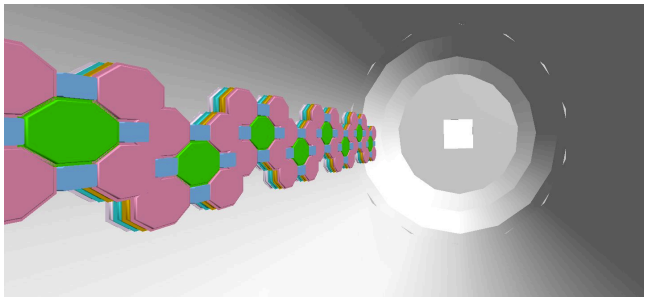

FIGURE 6. Water Walls Modules assembled in a Linear Array that can wrap around the interior of a space habitat pressure vessel. Drawn by Renée L. Matossian

F. The Nitrogen Economy

Nitrogen plays a key role in the processes within all the FO bags. It is so central to the Water Walls economy that it can be described as the currency of this ecosystem. Using the nitrogen cycle as a control algorithm is a key to managing and regulating the Water Walls production of consumables and of maintaining the equilibrium of this process. Understanding the nitrogen economy within the Water Walls ecosystem is critical to calibrating the size of the FO bags, the processes within them, and the process flows between different types of FO bags. TABLE 3b (in Section C) shows an early estimate of how the nitrogen economy influences the ratio of FO bags needed to support one algae bag.

This application of WW is the first operational solution for integrating the nitrogen buffer gas/nutrient production part of the ecosystem with a spacecraft ECLS system. The implementation of nitrogen cycling microbes in the WW ECLS system will make the system robust and capable to sustain many ecological and physical/chemical processes. Water Walls, using denitrification to liberate N_2 from urine, solids, and other wastes, is the only life support system on the horizon that addresses the nitrogen buffer gas that comprises nearly 80 percent of the Earth's breathable atmosphere at sea level. The minimum functionality and mission-specific approaches will produce sizing estimates for the FO bags, the tubing that connects them, and for the numbers of each type of bag needed to constitute a WW module. A detailed discussion of the nitrogen economy follows.

1. Nitrogen

Nitrogen occurs most commonly in pools consisting of N_2, N_2O, NH_4^+/NH_3, NO_3^-, and NO_2^- or organic-N. These pools exist throughout the various reservoirs (bags). Transformation reactions of N allow it to transfer from pool to pool, as well as from reservoir to reservoir (bag to bag). These reactions constitute the N-cycle, or N-economy of the WW system.

The total amount of N in a given reservoir (bag) at any one time represents a balance between N gains and losses. For example, N can be added from one bag (reservoir) to another through active pumping, or by biological fixation of N_2. The loss of N from the bags through denitrification represents a gain of N to the gaseous atmosphere (as N_2 or N_2O), but a loss to the bags. The transfer of N among the various bags constitutes the nitrogen cycle, or economy of the system.

The transfer of nitrogen--from one pool to another--proceeds within a bag, such as during ammonification (organic-N to NH_3). It represents a loss from one pool (organic-N) and a gain to another (NH_3), with no net change in the total nitrogen. These nitrogen transformation reactions constitute the nitrogen cycle at the bag (reservoir) level.

2. Nitrogen Fixation

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 them. Only a select few organisms, all of which are prokaryotic, possess the ability to grow in the absence of fixed nitrogen (Mancinelli et al, 1992). Nitrogen fixers can be divided into autotrophs and heterotrophs, depending on their source of carbon. They can be further sub-divided and designated as free-living (e.g., cyanobacteria) or symbiotic (Rhizobia found in nodules on plant roots). Nitrogen fixation is performed by Nitrogenase, an enzyme. Nitrogenase catalyzes the overall reaction:

$$N_2 + 8e^- + 8H^+ + 16\ ATP \text{ to } 2NH_3 + H_2 + 16ADP + 16\ Pi$$

Sixteen molecules of Adenosine Tri-Phosphate (ATP) are required to break the nitrogen to nitrogen triple bond in N_2 The requirement for such a large number of ATP molecules makes biological nitrogen fixation a very energy expensive process. Because of the high-energy cost, organisms preferentially use fixed nitrogen when it is available and only fix nitrogen when the demand exceeds the supply. Because in the WW system there will be a plentiful supply of fixed nitrogen from the blackwater and graywater bags, we anticipate that N-fixation rates will be low or non-existent.

3. Ammonification

Numerous organisms perform ammonification, the enzymatic process of organic-N conversion to NH_4+. Because there is a wide array of N-containing organic compounds belonging to different chemical classes, a correspondingly wide array of enzymes is required that break them down to produce NH_4+. In the WW bag system, the graywater and blackwater bags will support active, ongoing ammonification. The NH_4+ (or NH_3) may be used as "fertilizer" for the algae bags if no nitrogen fixing cyanobacteria are grown in co-culture in the "algae" bags. The algae used in this system will be species of *Chlorella*, which is a well-characterized fast growing green alga.

4. N-Assimilation

Nitrogen assimilation is the conversion of NH_3 or NH_4+ to organic-N that organisms use for the production of biomass. The NH_3 produced by nitrogen fixation, or ammonification, is assimilated in a series of enzymatically-catalyzed reactions. Some organisms, such as the algae used in the WW system have the ability to assimilate NO_3^-. In these organisms the NO_3^- reduces to NO_2^- by an assimilatory nitrate reductase. This reaction is followed by the reduction of NO_2– to NH_3 by an assimilatory nitrite reductase. The NH_3 so formed is then used in proteins and nucleic acids, for example.

5. Nitrification

Nitrification consists of the oxidation of NH_4^+ to NO_2^- and then the NO_2^- to NO_3^-. Chemoautotrophic bacteria (autotrophs obtaining their energy from the oxidation of inorganic compounds) typically perform this nitrification. Nitrosomonas perform the first step NH_4^+ to NO_2^-. Nitrobacter performs the second step NO_2^- to NO_3^-. These nitrifiers synthesize all of their cellular constituents from CO_2 via the Calvin cycle and an incomplete tricarboxylic acid (TCA) cycle. Although these two types of chemoautotrophic bacteria principally carry out nitrification in nature, a variety of heterotrophic bacteria and fungi are also capable of nitrification.

6. Denitrification in Water Walls

Denitrification is the dissimilatory reduction of Nitrate (NO_3^-) to nitrous oxide (N_2O) or dinitrogen (N_2). It occurs among a diverse array of microbes. Because it is coupled to the production of adenosine tri phosphate (ATP) and electron transfer occurs *via* the cytochrome system, it is anaerobic respiration. The process usually occurs under anaerobic conditions, but can occur in primarily aerobic systems that contain anaerobic microsites (Mancinelli et al, 1992) such as may occur in the Water Walls bags (e.g., blackwater and graywater bags). With few exceptions, denitrifiers preferentially use O_2 as their terminal electron acceptor, and when respiring O_2, function as aerobes. It is only when O_2 is depleted and there are sufficient electron donors in the environment that they respire NOx and become anaerobes, thus relegating the nitrogen oxides to a secondary level.

The organism generates cellular energy (ATP) by the transport of electrons *via* the cytochrome system from an organic or inorganic source to NO_3^-, or to a more reduced nitrogen oxide (e.g., NO_2^-, NO, N_2O) derived from NO_3^-. Nitrate serves as an electron acceptor in an electron transport chain. By accepting electrons, it becomes more reduced and forms a new acceptor of electrons. This process continues until N_2O or N_2 is formed. The nitrogen oxides that form during the process serve as electron acceptors during denitrification and proceed along the following pathway: $2NO_3^- > 2NO2^- > 2[NO] > N_2O > N_2$. An enzyme catalyzes each step of this pathway.

Heterotrophic denitrifiers use a wide variety of organic compounds (e.g., alcohols and organic acids) as initial electron donors for denitrification. The electrons are used to reduce NO_3^- to NO_2^-. This reaction is catalyzed by dissimilatory nitrate reductases, distinct from the assimilatory nitrate reductases in form and function. For example, neither the production nor the activity of the assimilatory reductases is affected by O_2 in most organisms, whereas dissimilatory nitrate reductases are usually not produced in the presence of O_2, nor do they function properly under aerobic conditions. In addition, the presence or absence of NH_4+ does not influence dissimilatory nitrate reductases, but does regulate the synthesis of assimilatory nitrate reductases. In fact, many denitrifiers can also assimilate nitrate and incorporate it into biomass while obtaining the energy for performing these reactions by denitrification. They produce two separate enzyme systems that are independently operated and regulated that both use NO_3^- as a

substrate and reduce it to NO_2—.

III. Key to Success: Incrementally Consuming the System – Not Driving it to Failure

Instead of wearing out and failing at predictable but unbeatable intervals like electro-mechanical systems, the Water Walls FO bags or tanks are consumables; they depend upon predictable and regular exhaustion of capacity to perform properly. They process a time period's increment of effluent and so use up the capacity of one set of FO bags. Then, the Water Walls operating system switches the processing to the second set, then the third set, and so on. . . . If the crew uses up all the installed FO bags during the course of the mission, they can swap them out for stored bags. Similarly, at the end of the mission, for a truly reusable deep space vehicle, the Water Walls architecture design enables replacement of the FO bags for a completely restored system, ready for a new mission.

A. Preparing the Water Walls System

Preparing the Water Walls system for use involves charging most of the FO bags with water. It is not necessary to launch the habitat with the water; the idea is to launch the water separately and then pump it into the spacecraft for the Water Walls system. In that way, the radiation shielding is in place from the outset. It also reduces the initial launch mass to LEO for the deep space vehicle launched on an SLS or other heavy lift launcher; the water can be launched on a much less expensive EELV or equivalent. We estimate the H_2O needed for WW for a deep space mission is on the order of 20 to 70 metric tons (70 tons is about 20% of the current requirement to support the ISS 6 person crew for its 10 year life, assuming a 80% water recovery ratio for the ISS water recycling system).

B. Risks of this Approach

The key risks of this approach to developing WW include:

- The FO processes suffer efficiency reductions in 0-G due to increased concentration polarization. The flight experiment on STS-135 conducted by the PI demonstrated up to a 50% reduction in flux rate in microgravity when compared to a 1 g environment,
- The sizing and proportional ratios of FO bags may not yield simple, modular solutions,
- The biological stability of solid products ($CaCO_3$, dried waste) remains to be determined.
- The suitability and safety of the algae/cyanobacteria grown from blackwater effluent for eating and the N_2 balance remains to be proven.
- Odors and odor control remain to be addressed,
- Punctures and fluid leakages remain to be addressed.

IV. Conclusion

The Water Walls Life Support Architecture marks a new approach to sustaining space crews over interplanetary distances and the time durations required for their spacecraft to travel those distances. To develop this new departure, it was necessary to let go of some of the most devoutly held beliefs in "high technology" in general and in aerospace engineering in particular. Those beliefs generally revolve around creating better, more complex, and higher performing machines to replace the natural and ecological processes that keep the Earth's ecosystem living, growing, and resilient under environmental stressors. What Water Walls does is rather than pursue the mechanical path, to emulate instead the Earth's ecosystem that by its very nature is massively redundant and therefore highly reliable.

Having stated this high level principle, it is necessary to qualify this summation by observing that creating the Water Walls system as a Life Support Architecture is proving extremely challenging. The major issue for Water Walls looking ahead is how to build it into a comprehensive life support program. FIGURE 7 shows the current and proposed components of the Water Walls initiative, including some projects such as the Ames-JPL Air Team's Humidity Control project that uses somewhat passive means to a different purpose, in this case dehumidifying air for better performance of the Sabatier Reactor downstream in removing CO_2. The current strategy does not yet afford funding to cover all processes within each Process Block, nor does it show the potential Higher Plant Growth Block 5. Even where a process within a block is funded, that support has been very limited, both in amount and in duration.

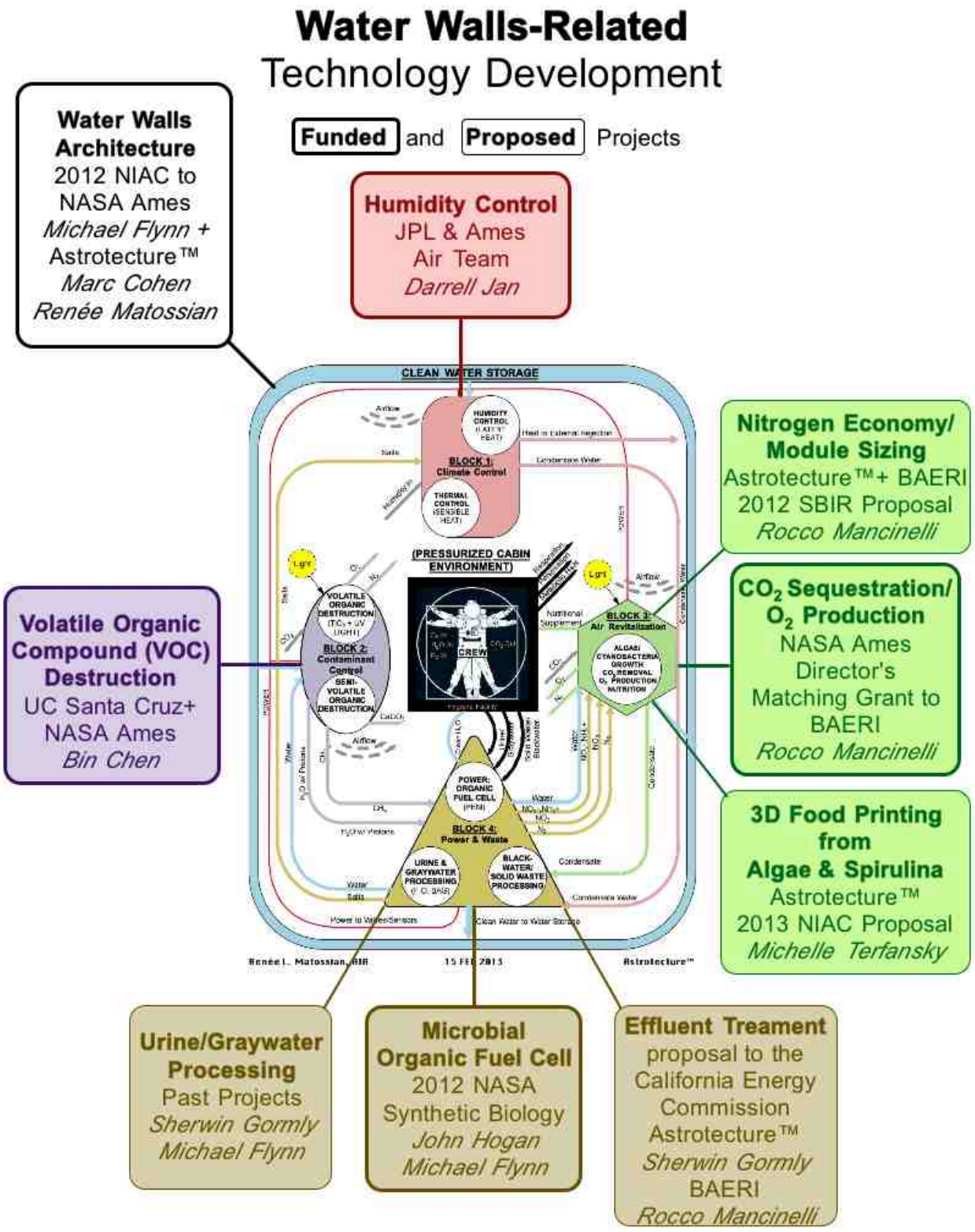

FIGURE 7. Allocation of Funded and Proposed Water Walls-related Projects

Beyond this discussion of the Life Support Process Blocks and their subsystems, a major innovation ahead will be designing the architecture for the living and working environment that enables integrating Water Walls into

the spacecraft crew cabin or other space habitat. Incorporating WW *literally* into the wall cross-section or fabric is only one potential feature of this far-reaching concept. The more significant aspect of Water Walls for spacecraft architecture is that by virtue of its modularization, it enables the integration of the overall system into a pressurized space module in ways that enhance all aspects of the crew living environment. WW offers the potential of radiation shielding integrated into the wall cross-section that can perform multiple functions for life support and climate control.

What is most important architecturally about Water Walls is that by laying out the passive life support system in advance of the structural and mechanical design of a space habitat module, it becomes eminently feasible to design the entire habitat ***around the life support system.*** This revelation means that space architects can move beyond the paradigm of "designing" habitats and crew cabins by being forced to retrofit arbitrarily designed "primary structure" in the form of pressure vessels (e.g. propellant tanks, or ISS-type four-standoff modules scaled to fit the Shuttle cargo bay). Instead, Water Walls gives NASA and commercial space exploration companies alike the first opportunity to conceive, design, engineer, and build a truly integrated human spacecraft that considers supporting all the human requirements as a first priority instead of as an afterthought.

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