SPACE CARGO TRANSPORT BAGS THROUGH MEMBRANE WATER TREATMENT ELEMENTS TO SPACE ARCHITECTURE BUILDING ELEMENT: A TOTAL PRODUCT SUSTAINABILITY AND LIFE CYCLE DESIGN OPTIMIZATION EXPERIMENT

Sherwin Gormly,[1] Michael Flynn,[2] and A. Scott Howe[3]

INTRODUCTION

The CTB Water Wall project is a maximal product life cycle utilization concept study by members of the space architecture design community. Its function is to demonstrate a human space activity Cargo Transport Bag (CTB) that becomes a primary water recycling membrane element after delivery of cargo, and then a permanent architectural building block for sustainable space habitation after its use in water treatment is complete. As such, it is intended as an experiment in radical life cycle product optimization in an extremely mass-constrained application environment (human space operations). It also introduces some fundamentally interesting concepts in architectural use of waste materials in extreme environments. Finally, it is in some ways a simple, tactile and visual demonstration of how far sustainable product design can be taken, if the motivation and technical justification are present.

KEY WORDS

*Author to provide

The Problem

In some ways, the special needs of the space logistics environment can and do work as perhaps the most extreme possible driver for total mass and material life cycle utilization. This most fully expresses itself as a driver for total sustainable mass balance in two ways: one, the area of water resources for life support; and, two, the area of bulk architectural building material delivery. In human space systems, launch costs radically constrain all mass (both water and product material mass used in life support and facility architecture) more than in any other conceivable design environment.

Launch costs are extremely hard to give specifically, in the way other freight delivery costs would be stated, but are generally are projected to be in the tens of thousands of U.S. dollars

[1]Hydration Technologies Innovations and Algae Systems.
[2]NASA Ames Research Center (ARC).
[3]NASA Jet Propulsion Laboratory (JPL).

per pound range, at the time of this study. This is because launch vehicles are generally billed as a percentage of total launch costs, not in a simple price per pound and/or volume. Thus the figures are never stated as a clear freight, but roughly back-calculated from total vehicle operation costs for whatever vehicle is used, and therefore remain quite high.

This mass and volume delivery constraint makes human space development an extreme sustainability problem that currently limits human access to the rest of the solar system and even effective continued operation in low Earth orbit (LEO). In effect, we have the rockets and all the other hardware to get there, but right now all we can afford to send are small robots for the most part. For humans to truly develop a space-faring civilization, it would help to lower direct launch cost by a substantial amount, but that will never be more than a small part of the solution. If launch costs are lowered more than one order of magnitude (10×, is considered possible) the mass of a human and baggage (250 lb, or 120 Kg) becomes affordable, if still a high price. However, the water, food, and shelter for that human to stay and work in space would still remain prohibitively expensive, even in LEO (i.e., on the current International Space Station).

For substantial human activity beyond LEO, or for that matter sustainable research and industrial activity in LEO, system closure and sustainability design must become the core of all human space design plans.

The Solution

For humans to enter space in a meaningful and sustainable way, as well as make the space endeavor meaningful and sustainable for the vast majority of humans still on Earth, human space design must be the quintessential sustainability technology design experiment. The study reported here is an experiment that addresses space architecture and long-term life support sustainability as the core of the human space endeavor and does so in a universally accessible and visual way.

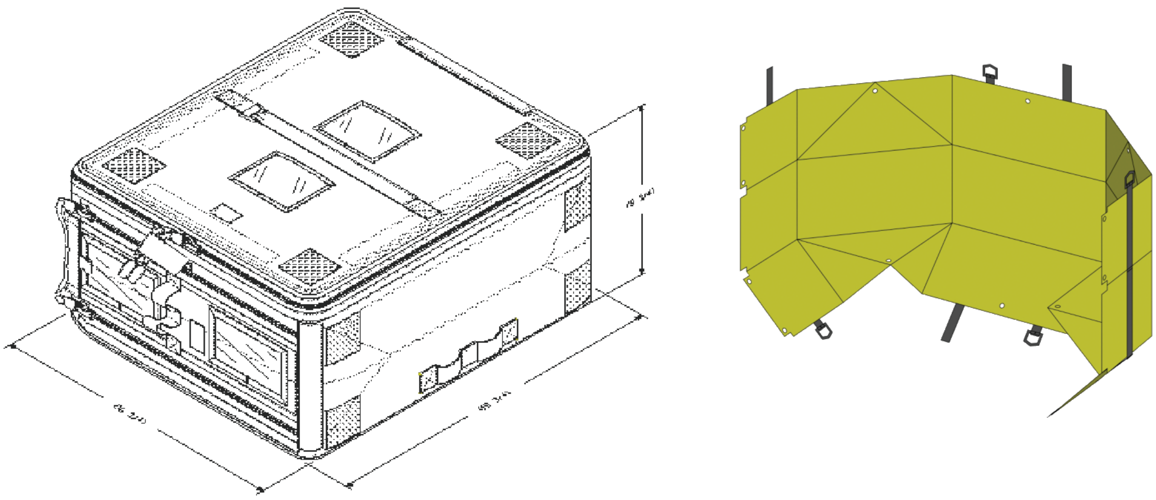
For sustainability to be addressed, any mass that would become waste must be recycled 100%. Water recycle must be effectively completely closed with no water, no matter how contaminated, ever being vented or down-massed (sent to a fiery fate over the oceans of Earth) simply as "waste." Additionally, any packaging and transport material must become useful in the building of the space structure, or retasked as an item for use in daily life in space. To date, system closure research and development has concentrated on air and water recycling in traditional "Life Support Equipment Racks." This traditional aerospace engineering hardware approach would seem to have reached its limits.

This study simultaneously retasked the primary packaging wastes—the Cargo Transport Bags (CTBs)—while optimizing water recycle efficiency, redundancy (safety), and sustainability, as well as addressing the architectural beneficial reuse of both the CTBs and the heavy solids containing 10% to 20% of the unrecoverable wastewater produced in the habitat. This integrated approach to total mass recovery and reuse starts by identifying the biggest drags on total delivered mass utilization, and then applies total lifecycle design logic to generating critical architectural and life support resources out of all of this mass.

What the CTB Water Wall is and How it Provides True Sustainability

The CTB Water Wall element is a transport bag that has membrane water treatment elements built into the support panels of the bag. When folded, the CTB functions like a suitcase that allows cargo to be transported into space. CTBs are specified to be a standardized

FIGURE 1. The Current and future foldable CTBs.



size and shape (Figure 1). Current CTBs retain their suitcase-like shape following delivery of cargo, and become a substantial waste mass. A foldable version of the CTB (Figure 2) has been proposed for use as blanketing and/or partition construction within the habitat. This approach has been outlined in a study called Logistics For Living.[1]

FIGURE 2. The CTB Water Wall Architecture Concept Model.

Why This Is a Potentially Important Experiment for Life Cycle Product Sustainability Design in General

So why should the Earth-based sustainable designer care about the CTB Water Wall project? The space operation environment for the CTB (the product in this case) is clearly unique and a small niche market for product design. However, the total life cycle conceptualization and utilization developed here is in and of itself a valuable case study in total product life cycle design. Thus, while not directly applicable to any given terrestrial application, the CTB Water Wall study is potentially most valuable as a conceptual experiment. Its primary contribution may be as a high value product case study in product life cycle sustainable design taken to the most extreme of application environment ever addressed by green product design principles. This more than anything else is the Earth relevance of this study.

This study provides a mechanism to look at product life cycle design and waste resource closure in a way that, while only being justifiable initially by the early cost points developed in human space flight, may also provide a model for design and resource utilization that can be more universally applicable in conceptual ways.

The CTB Water Wall superficially involves development of the FO membrane application and Logistics for Living CTB utilization scenario to address a specific extreme environment sustainability problem—total launch cost. But more fundamentally, it involves research into the stabilization of multimedia waste into high performance and consumer acceptable, prepackaged building resources. It does this through the active use of what amounts to an architectural smart material (the passive FO membrane process) and intelligent design of limited life packaging material (the CTB).

If done properly, this design concept could function as a model for producing products that operate as similar total life cycle utilization resources on earth. If this seems a stretch to some readers, it should be pointed out that the FO membrane water treatment bag is currently used in water emergency relief efforts, and is a simple plastic bag that takes on an active role to produce drinking water under severe and totally unsupported conditions (Figure 3). What if the same relief supply could also help to build a house?

This logic is applied to bulk industrial materials in industry, but rarely to crafted products, at least in the front-end design process. Many sustainable demonstration projects have used materials that are products (bottles in walls, railway ties in landscapes, and various interesting eco-art constructs), but how much better this would work if products used on a day-to-day basis (bags from the supper market, containers of many kinds, and limited life products like filters) were in fact purposefully (and profitably) designed for second and third uses in stable architecture.

The CTB Water Wall is a concrete example (something of a pun because calcium sulfate in urine quite literally can be precipitated as concrete and/or gypsum wall board by the membrane element) of design for complete life cycle utilization that will provide a high-profile and data-intensive sustainable design experiment. It will also make the concept of living and working in space relevant to the sustainability of developed human culture on Earth.

FIGURE 3. The simple FO hydration product in action in disaster relief.

THE CTB AND LOGISTICS FOR LIVING

Current Technology and Wasted Logistics: Logistics for Living

The use of the CTB as a potential architectural element predates and extends well beyond the CTB Water Wall concept study alone. The CTB Water Wall is only one option for how to construct a CTB for full life cycle utilization within the human space habitat, albeit one of the most interesting from a comprehensive design perspective.

While the CTB Water Wall is currently the most advanced concept in CTB life cycle design, the use of cargo transport bags as architectural elements has been being developed for several years under a program referred to as Logistics for Living. This program has been assessing how to integrate all incoming logistic, in the form of CTB packaged supplies, to best optimize their use in both space habitat design and radiation protection. Their function is considered both while the supplies are still packed in them, as well as their use as habitat useful architectural element after their useful life as cargo transport packaging is complete (Figure 4 and Figure 5).

It should be pointed out for complete accuracy that we do use the term CTB somewhat loosely in this study when describing application of the CTB Water Wall concept to what is in fact the whole range of standardized fabric suitcases used to transport cargo for human space flight. More correctly the term CTB applies specifically only to the smallest of four standard sized transport containers currently in use for the International Space Station and other human rated vehicles with international crews.

However, the four sized containers are all more or less constructed of similar material, in similar ways, and for similar functions. So in describing our study we use the term to extend to the whole class of containers in the future from a design perspective, though for the sake of this study only the smallest unit (i.e. the properly named CTB) is used for consistency and accuracy in modeling our concept. Thus, the CTB

FIGURE 4. Optimized logistics packing analysis for space habitats.

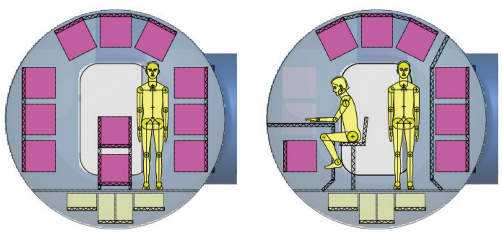
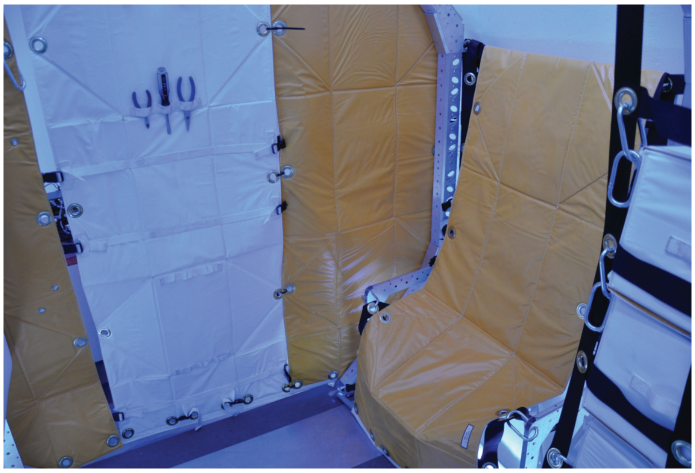


FIGURE 5. Optimized logistics packing analysis for space habitats.



(properly named) is the standard-sized unit we use here and for the projected flight experiments to follow, and thus serves the immediate needs of the Logistics for Living goals of immediately useful real world hardware.

The Logistics for Living design process proposes the reuse of logistics shipping/packaging material in general, and in particular the pre-design of those materials to be user-friendly and even attractive as housekeeping and internal architecture elements through the life cycle not only of the product (the shipping container) but also the service life of the habitat as well. These materials do this best by becoming permanent, attractive, and useful elements of the internal spacecraft habitat environment—before and after their primary use is complete.

THE FO BAG AND THE WATER WALL CONCEPT (INDEPENDENT OF THE CTB)

The History of the FO Bag and Flight Experiment

The concept of forward osmosis membrane processing of water has developed for a number of applications. Prior to NASA's development of the technology for life support applications, FO was developed for use in the food processing industry to concentrate fruit and vegetable juices[2–5] and was then applied for direct desalination[6–8] of brackish water and seawater. A wastewater treatment process using FO technology was also developed by Hydration Technology Innovations (HTI) to treat landfill leachate.[9] A version of this landfill leachate treatment system was later developed into the first FO-based NASA test apparatus for habitat water recycling. More recently FO has also been used as a renewable energy technology where the potential energy between freshwater, such as a river, and contaminated water, is converted into electricity.[10–11] The CTB water wall has evolved from this now well-established new technology.

Initially (and perhaps eventually as well) the Water Wall was to be composed of a series of membrane bags packed as dry elements integrated into an inflatable habitat structure's wall. After launch and deployment, the wall membrane elements would be filled with water and maintained as a freshwater supply and radiation shield. As the initial water supply is consumed, the depleted treatment bags are filled with wastewater and take on a dual role as both active forward osmosis (FO) water treatment and water wall radiation shielding.

When an FO element is exhausted, fouled, and/or stalled by excessive waste-side residuals, treatment ceases in that element and is moved on to the next bag in the wall. Exhausted FO bag elements are drained, fluids are mixed with feces, solid organic wastes, and/or advanced water treatment residuals and re-injected for sludge treatment, or simple curing in place as stable solids.

The bags now work as organic/solids composting digesters/driers. Anaerobic digestion will produce CO_2 and CH_4 (methane), which will be harvested, compressed, and processed for use in O_2 generation. Methanogenic composting will reduce the water content and stabilize the biosolids, producing humus and recovering a substantial percentage of the remaining water.

Nitrogen-rich, urine-dominated brines, typical of a transit mission waste profile (i.e., waste waters collected in free space rather than on a planetary surface), combined with thermally stabilized solids (charcoal and/or ash) would be aerobically treated to drive off ammonia- and odor-causing VOCs and dried to "sheet-rock" like material in place. Once the humus or urine salts (sheet rock) are biologically stable, the bags become a permanent hydrocarbon/hydrated precipitate radiation shield.

Uses as Is: The FO Bag with Activated Carbon for Urine or FO only or as Marketed for Seawater

The basis for the inflatable habitat Water Wall concept was the passive FO hydration bag discussed earlier. This product is a commercial and disaster relief agency oriented product, independent of space operation priorities in form and content. The commercial version of this product has in turn been used as a model for the development of emergency urine recycle and seawater desalination options, for use in human space operations.[12]

The simple FO hydration bag, when combined with activated carbon (AC) provides an effective way to recycle more the 3 times it's weight in urine for in-space water emergencies. The FO bag and sugar part of this emergency urine recovery processor (i.e., FO bag only, without AC) can provide the same function for seawater desalination in post-landing, delayed recovery at sea, water emergencies. The same FO bag would yield 10 times its weight in drinking fluid when treating contaminated fresh water in an on-land survival scenario. Thus, the FO bag is currently being actively considered for use in survival rations for space flight crews and is undergoing flight tests accordingly.

The operation of both the inflatable Water Wall FO element and those to be used in the CTBs are essentially identical to the urine recovery and seawater recovery bags. These urine and seawater recovery bags are themselves essentially identical to the commercial disaster relief products, with only the materials used in the outer watertight plastic envelop bags being slightly modified to meet NASA flight flammability and off-gassing standards. As a result, the testing and development of the FO bags for water emergencies related to space flight crews will provide a proof of concept for the technology that will then apply to uses such as the inflatable wall applications and the sustainable retasking of CTBs.

The Water Wall as an Inflatable Habitat Concept

The Water Wall concept originally proposed in the inflatable habitat wall arrangement is shown in Figure 6. The fabric shown has FO membrane bags quilted into it and would function as an active membrane water processor when incorporated into the wall of the habitat. Inflatable, soft walled habitats could take many forms, as shown in the Figure 7.

This initial notion of building the FO membrane based Water Wall into the permanent structure prior to launch is attractive, and may be valuable in many mission scenarios. However, inclusion of the same concept into a life cycle waste management solution may be even more attractive and sustainable. Considering that the CTB construction material is similar to the material proposed for some layers of the inflatable structure wall, and will

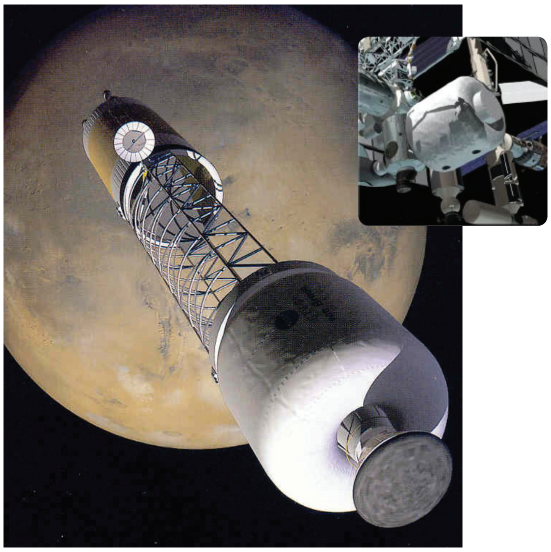
FIGURE 6. Pictured is an example of how an architectural piece of active FO membrane would be quilted into an appropriate inflatable habitat wall structure fabric.

be selected from a limited set of flight-rated materials—of which the FO bag material is now included—it became a natural progression to ask the question, could the two products somehow be merged?

BRINGING THE TWO TOGETHER

By combining the flexible options in architecture presented by Logistics for Living with both the tested functional performance of the hydration bag and the additional Water Wall concepts facilitated by the FO bags, we can move directly into the development of a designer waste product used to build whole habitat. These CTBs will have active life support functions built in at the substrate level. Once its active life support function is accomplished, the CTBs become the basic building blocks for multiple parts of the "finished" but continually evolving habitat. All the functions are individually demonstrated and outlined, but providing a real tactile model was of the greatest importance for this concept in this study.

FIGURE 7. Inflatable Habitat Architectural Concepts (Images by John Frassanito & Associates, Courtesy of NASA on line resources).



The Advantages of a Synergistic Experiment for CTB Water Wall

The combined CTB Water Wall proposed life cycle flow will be outlined here and is available elsewhere,[13] however, the advantages to this approach became apparent even in the experimental phase of evaluating the technology. For this reason it is important to note the manageable modularity that is achieved by the CTB Water Wall experiment itself.

The CTB is the smallest of the current space transport packages in standard use for the International Space Station. As such, a life support experiment that inherently fits into the lining of the CTB is the most effective life support system experiment possible from a launch cost and materials handling perspective. It effectively provides a free launch for a fundamental life support equipment experiment.

If the future of space habitats is inflatable, then constructing the life support systems to fit into the lining of a flexible suitcase is clearly an advantage, but a more subtle advantage is in flight safety. If the experiment is constructed of space flight-rated materials from the start (i.e., the flight-rated CTB and the flight-rated FO bag materials) and shipped as an integral part of the packing material for food and supplies, all flight materials considerations are met for uses of the technology by default. The elegance of this approach to experimenting in new spacecraft construction methods is inherently evident from a design perspective, and speaks well of the concept from the start.

The Life Cycle Concept for the Mature Combined CTB Water Wall

To understand the dynamic functions of the CTB Water Wall element it is helpful to better understand how the element would flow through the crew living environment while it passes through the stages of its functional life. Upon arrival and unpacking, the initial CTB Water

Wall water contents could be directly harvested to provide a supply of fresh water, rather than shipping that water in dedicated containers. Once the CTB Water Wall is unpacked and drained of its initial shipping water, it is unfolded and positioned in an area where wastewater is to be treated, and walls of layered CTB blankets are most appropriate.

To provide the best near-term impact it is likely that the CTB Water Walls would be initially stored and then used as wastewater treatment in the multi-layered walls of a crew shelter room. This room would act as the "storm shelter" during solar flares. It should include the primary sanitary facilities (for obvious convenience and safety for the crew) and thus will be close to urine collection and other sanitary plumbing within the habitat. This approach would concentrate the Water Wall shielding effect early.

The CTB Water Walls partitioning this shelter would be a natural accumulation point for resources, as both the freshwater supply CTBs and the CTBs actively being used for water treatment and handling would be naturally concentrated in this location. By using the CTB Water Wall in this location, maximum water-shielding density effects would be concentrated early in the habitat's use, and would remain stable as new supplies are brought in and old CTBs removed.

As more and more CTBs are received and processed through their useful life, both as water storage and active treatment, exhausted bags will be drained, re-injected with wet solids residuals, cured to stable solids before being removed from the active use "storm shelter" area to other permanent locations. These other locations may be within the exterior wall of the habitat, or outside in the accumulating shell of the habitat structure. As this occurs other areas of the habitat are gradually better protected.

The concentrating of solids wastes in the CTBs, and then their use as both radiation and micrometeorite shielding on the exterior of the habitat, is probably most appealing as the post water treatment fate of the CTB elements. In this mode, the Water Wall CTBs would contain waste on the inside of the habitat for only a short period of time.

Their use in a robust, attractive, functional, and flexible tiling pattern on the exterior of the habitat is explored by the architect Raul Polit Casillas. This approach would provide an accumulating shell of flexible but robust shielding over the life of the free space habitat, while being applied robotically without the need for extra-vehicular activities (EVAs) by crews. The final design effect is one of a clean white sandbagged cylinder, with no hint of the contents, and is surprisingly clean of line and texture visually.

Because the solids are cured but still wet prior to placement they will likely become more rigid after placement as well (due to freeze-drying effects), and be filled with viable soil rather than wastewater sludge if recovered later for use in plant growth. This final use as soil may be more an aesthetic consideration than a practical one. It is more pleasant for the crew to contemplate being surrounded by a sandbagged wall of viable soil than uncured waste materials.

It should also be noted that much of the garbage accumulated during human space operation is plastic, and this waste might best be handled using heat melt compacters to produce stable plastic encapsulated wastes. These plastic wastes could be formed so as to be easily installed into the areas of the CTBs lining not used for biological waste solids. The hydrocarbon nature of these wastes would also act as water-based radiation shielding (both rated on hydrogen content). Thus, during the wastewater solids curing process, plastic-dominated solid wastes could be formed to fill in, and balance out, the water volume lost to solid waste.

The full life cycle functions of the CTB Water Wall from water storage, through use as a primary wastewater processor, and finally for solid waste accumulation and stabilization, is covered in several technical publications related to the Water Wall concept.[13] The functional performance elements of the FO bag water treatment both terrestrially and in microgravity are also well-documented elsewhere. Both are only outlined here to give an idea of how the CTB Water Wall will flow through the daily life of a space crewmember. What follows is what that could look and feel like.

The CTB Water Wall Architecture Concept Design Study's Architectural Element Demonstration Model

The current study relates more directly to the architectural nature of the CTB Water Wall synergy than water treatment or functional aspects of the CTB. As such, it relates to the real-world look and feel of a CTB Water Wall model as a functional architecture element, and as a day-to-day part of the crew environment. Beyond working as we know it can to transport supplies and treat water, what will it look and feel like? Is it an attractive element to the crew environment and/or the long-term construction of the habitat? This can only be answered by construction of visual and tactile models that can be experienced in real-world ways. This study's primary objective was to provide this experience.

The CTB Water Wall is initially seen and experienced as a cargo transport container (Figure 8). It is a specified size, in this case 42.5 cm (16.75 inches) by 50 cm (19.75 inches) by 25 cm (9.75 inches). This constitutes a current packing size standard for the International Space Station use, but is in no other way critical from a design perspective.

Once the cargo is removed from the CTB the bag is unfolded (Figure 9). The unfolded CTB will present input and output quick disconnect ¼″ nipples servicing both the reject and permeate (product) side of the water treatment membranes in the lining of the CTB (Figure 10). Any initially, stored fresh water that might be transported in the CTB is removed from these plumbing accesses points. Then these points will be attached to the urine and humidity condensate treatment loop of the space habitat water treatment system, and provide the first stage of water recovery on these waste streams when attached.

When the treatment function of the membrane bags within the lining of the CTB (Figure 11) is exhausted, wet solids are pumped in and permanent caps are affixed. Curing time is allowed and monitored, and then the expended CTB Water Wall is moved to its permanent location.

FIGURE 8. Folded CTB Water Wall Architecture Element Demonstrator with the current space flight-rated FO bag alongside for scale.

FIGURE 9. Two unfolded CTBs.

FIGURE 10. CTB Water Wall input ports for forward osmosis treatment and recovery of wastewater.

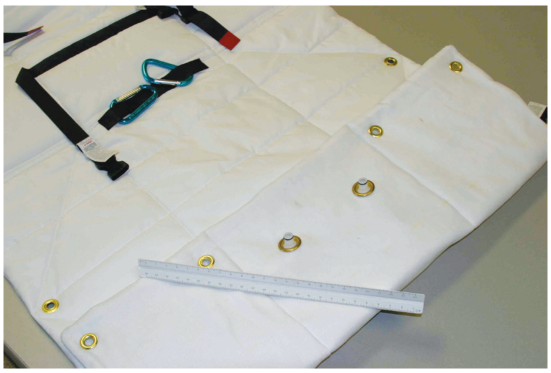


FIGURE 11. Testing of a three-bag array of FO bags prior to their insertion into the lining of a folded CTB Water Wall element.

The configuration for internal use during fresh water storage or active water treatment within the habitat can be seen in Figures 12 and 13. Once stability is achieved, the expended CTBs are passed through compact cargo airlock and robotically affixed to the exterior of the habitat (Figure 14).

IMPLICATIONS FOR SUSTAINABLE PRODUCT LIFE CYCLE DESIGN

Not Just the CTB Water Wall but Assessing the Multiuse Life of All Space Cargo

When appraising the function of the CTB Water Wall study, it is important to understand it in the larger context of multi-use life cycle sustainability design and research. The specialization dictated by spacecraft engineering project management methods and paradigms tends to require that all things be assessed using a strict reductionist mentality leading to the simplest set of performance parameters possible, becoming overridingly directive in design decision making. This has resulted in a lot of highly-refined mechanisms that when put together produce an overly complicated, hugely expensive, and underperforming habitat life support system that is difficult to manage and control. In short, space life support has hit a design wall resulting from old technology being developed into ever more complex mechanical system designs based on the "life support equipment" model. This is not an unfamiliar problem to the sustainable water design engineer, scientist, or green architect working in the rest of society.

FIGURE 12. CTB Water Wall Architecture Demonstrator seen internally mounted in the D-RATs habitat demonstration unit August–September, 2011.

FIGURE 13. End close-up of CTB Water Wall Architecture Demonstrator seen internally mounted on the D-RATs habitat demonstration unit August–September, 2011.

The problem is simple: the total water recovery from current systems is on the order of 80% or better. Solid waste recovery is currently 0%, with the exception of the solids that become exhaled water after being eaten (more on that shortly). This does not mean that the crew ends up short of the 20% of the water that is lost to water recycling inefficiency, because the carbohydrates in food become CO_2 and H_2O, and this more than makes up for the water loss due to treatment. What is a problem is that the 20% water and wastewater solids loss to the whole habitat system with each water treatment cycle becomes waste in every respect (particularly mass), and this is added to 100% of the wet food and packaging waste mass as a total mass loss to the mission.

FIGURE 14. Exterior CTB Mounting Demonstration.

The integration of well-designed passive membrane systems utilizing FO could lower the water loss rate to below 10%, but more importantly could utilize the "lost" water and solid waste to accumulate total mass in a useful way, and drastically lower the required launch mass of a properly-shielded spacecraft over time in the process. Also, it will do so without asking wastewater treatment processes to extract more water from waste than is practical or desirable.

Both CTB Logistics for Living and Water Wall as Mechanisms for Accumulating and Beneficially Retasking all Mass as Opposed to Wasting It

The retasking of the last 10% to 20% of the water to absorb and process the mass of the solids, and thus retask all the mass supplied to the spacecraft, may be more important than simply concentrating design efforts on more efficient water treatment systems. This is because sustainability in space—as on Earth—is never a single variable problem, and wastewater solids handing is certainly not.

Thus the road to the planets and the stars is not paved with gleaming new machines that will squeeze 99.9% of the water out of urine salts, because it is probably impossible to operationally achieve much better than 90% water recovery from any water processor processing urine. It is probably a physical impossibility get much over 95% even in the lab, due to the dissolved solids content of urine. As one gets over 90%, the perception end points of many things in the waste become a concern. Also, it is probably undesirable to operate above 90% anyway, based on the properties of the waste solids produced. Urine-dominated wastewaters that are concentrated this much tend to take on some extremely undesirable physical and chemical properties. Making urine salt into hazardous waste is not a sustainable solution for space flight, or anywhere else.

Optimal sustainability can be achieved by shipping only food and building your spacecraft sustainably by converting 10% to 20% of your water and 100% of your biomass from rations into building material. The biggest untapped resource in space—as on Earth—is our own waste, and greater treatment efficiency must eventually give way to sustainable reuse of materials as the primary design driver. The CTB Water Wall study offers a new direction pointing the way.

CONCLUSIONS

Assessment of the CTB Water Wall Concept to Date

To date:

1. The foldable CTB—with or without contents—has been well illustrated.
2. The FO membrane water treatment bag technology has been successfully tested in space, and demonstrated in the worst of conditions terrestrially.

And

3. The combined CTB Water Wall concept has been illustrated and demonstrated as an architectural element for space habitat design.

All that remains is integrated CTB Water Wall development to be completed and followed by testing and implementation in space. A national human spaceflight program should formally adopt this effort at this time. If it does so it will provide human space flight with sustainability tools and research justifications at the same time, and in ways that are currently lacking.

Future Direction for Project Research Both in Space and on Earth

It is often perceived that space flight is the ultimate unsustainable "gray" technology, but if it is to continue, nothing could be further from the truth. As a sustainability experiment, human space flight is both the most unforgiving and most clearly productive venue for sustainable technology development.

The life cycle design of a product that is, in effect, a grocery bag that can morphed into a water treatment system, and finally compost itself into a Gaian radiation shield, awaiting use as soil on a new and barren world, is in some ways the ultimate expression of sustainability research. It is art and architecture and engineering science, and what we should expect from the endeavor of human space flight. Based on the sustainability constraints of the space environment, it may be the only way to make an interplanetary human civilization possible. It also may provide a conceptual model for the ultimate sustainable life cycle product design exercise.

REFERENCES

1. Howe, A. Logistics for Living. *Proceedings of the 40th International Conference on Environmental Systems, American Institute of Aeronautics and Astronautics*, Barcelona, Spain, July 2010.
2. Beaudry, E., and K. Lampi. (1990). Membrane technology for direct osmosis concentration of fruit juices, *Food Technology*, 44, 121.
3. Wrolstand, R., M. McDaniel, R. Durst, N. Micheals, K. Lampi, and E. Beaudry. (1993). Composition and sensory characterization of red raspberry juice concentrate by direct-osmosis or evaporation, *Journal of Food Science*, 58, 633–637.
4. Petrotos, K., P. Quantick, and H. Petropakis. (1999). Direct osmotic concentration of tomato juice in tubular membrane-model configuration. II. The effect of using clarified tomato juice on the process performance, *Journal of Membrane Science*, 160, 171–177.
5. Petrotos, K., P. Quantick, and H. Petropakis. (1998). Direct osmotic concentration of tomato juice in tubular membrane-model configuration. I. The effect of certain basic process parameters on the process performance, *Journal of Membrane Science*, 150, 99–110.
6. Kravath, R., and J. Davis. (1975). Desalination of seawater by direct osmosis, *Desalination*, 16, 151–155.
7. Biberdorf, C. (2004). Filter in a pouch, *The Warrior*, July–August 3.
8. McCutcheon, J., R. McGinnis, and M. Elimelech. (2005). A novel ammonia-carbon dioxide forward (direct) osmosis desalination process, *Desalination*, 174, 1–11.
9. York, R., R. Thiel, and E. Beaudry. (1999). Full-scale experience of direct ososis concentration applied to leachate management, *Proceeding of Sardinia '99 Seventh International Waste Management and Landfill Symposium*, S. Margherita di Pula, Cagliari, Sardinia, Italy, 1999.
10. Gormly, S., J. Herron, M. Flynn, et. al. (2011). Forward osmosis for application in sustainable energy development, *Desalination and Water Treatment*, 27, 327–333.
11. Sandvik, O., P. Hersleth, and K. Seelos. (2009). The forces of osmosis and tidal currents, *HYDRO2009*, October.
12. Gormly, S., and M. Flynn. (2007). Lightweight Contingency Urine Recovery System Concept Development, *Proceedings of the 37th International Conference on Environmental Systems*, Chicago, IL SAE Publication #2007-01-3037.
13. Gormly, S., M. Flynn, A. Polonsky. (2010). Membrane Based Habitat Wall Architectures for Life Support and Evolving Structures, Sherwin Gormly, Michael Flynn, Alex Polonsky. *Proceedings of the 40th International Conference on Environmental Systems*, Barcelona, Spain, AIAA Publication.