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Forward Osmosis Cargo Transfer Bag

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Abstract

All human space missions, regardless of destination, require significant logistical mass and volume. The amount required is a function of the mission duration. Reducing this logistical mass and volume by reusing items that would otherwise become trash can reduce launch weight and consequently mission costs. This paper describes a logistics reduction technology based on repurposing International Space Station (ISS) Crew Transfer Bags (CTB).

CTBs are fabric cargo containers, which conform to specific dimensional and material requirements for space flight. This paper describes the development of a Forward Osmosis Cargo Transfer Bag (FO-CTB) that can be reused on orbit to provide radiation sheading and water recycling capacity. The design, construction and testing of a prototype FO-CTB at the Desert Research and Technology Studies (D-Rats) Habitat Demonstration Unit (HDU) in 2011 is described. In addition, a summary of the results of a flight experiment performed to evaluate the effect of microgravity on the forward osmosis (FO) membrane bags used in the FO-CTB is also discussed. Future plans for the continued development of the FO-CTB are also discussed.

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Nomenclature

FO-CTB	Forward Osmosis Cargo Transfer Bag
CTB	Cargo Transfer Bag
LEO	Low Earth Orbit
D-Rats	Desert Research and Technology Studies
L2L	Logistics to Living
HDU	Habitat Demonstration Unit
ISS	International Space Station
FO	Forward Osmosis
GAC	Granular Activated Carbon
HTI	Hydration Technologies Innovations
NGLS	Next Generation Life Support
FOST	Forward Osmosis Secondary Treatment
DTO	Detailed Test Objective
FY	Fiscal Year

Introduction

This paper describes a Logistic to Living (L2L) evaluation for repurposing or converting space flight logistical items into useful crew items after they have completed their primary logistics function. The intent is that by repurposing items, additional items do not have to be launched and overall launch mass will be decreased. L2L will enable payloads to be used more effectively through reuse and rearrangement of logistical components.

The L2L concept discussed in this paper is based on cargo transfer bags (CTBs) which are currently used to transfer cargo to the ISS. For a 6-month mission, a crew of four typically uses hundreds of CTBs. These CTBs are used for on-orbit transfer and storage but eventually becomes trash after use. This paper discusses the reuse of the CTBs to provide multiple functions such as radiation protection, life support capacity, and structural elements in addition to their primary use as cargo transfer bags.

The LTL concept redesigns CTBs to enable disassembly on-orbit (unfolding). The deconstructed CTBs are then filled with water and reused for radiation shielding and life support functions. These CTBs are modified to include a inner bladder that allows them to be filled with water. The CTB can then be used as a radiation protection water wall. In addition, if the CTB bladder is composed of a forward osmosis (FO) membrane the CTBs can then be used to recycle wastewater.

A prototype FO-CTB was tested this August 2011 in the D-Rats HDU field demonstration project. This testing demonstrated FO water recycling bags integrated into a CTB simulator. The primary objectives of this testing was to construct the CTB, integrate it within the HDU, and demonstrate basic function as a water treatment system. Testing was composed of processing simulated wastewater.

A flight-test of a stand-alone FO bag, the functional element of the FO-CTB, was completed as a sortie payload Shuttle Mission, STS-135 in early July 2011. This mission tested a flight qualified version of the FO bags used in the FO-CTB. The primary objective of this test was to demonstrate that FO functions as expected in microgravity. The flight version of the bag is called the Forward Osmosis Bag (FOB).

The main goal of the FOB flight experiment was to investigate the forward osmosis membrane in spaceflight environment and compare its performance against ground reference controls. The flight evaluated the flux of water across the forward osmosis membrane in reduced gravity using a combination of indicator dyes. Samples were collected and specific ion analysis was conducted to determine ion rejections. An evaluation of the effects of mechanical mixing upon the flux rate was also completed. A summary of these results is provided in this paper.

Background

The FO-CTB is based on a technique called forward osmosis (FO). FO is a process where the osmotic potential between two fluids of differing solute/solvent concentrations equalize by the movement of solvent from the less concentrated solution to the more concentrated solution [1-4]. This is typically accomplished through the use of a semi-permeable membrane that separates the two solutions.

In wastewater treatment applications where the solvent is usually water and the solutes are the contaminants, the semi-permeable membrane allows the flux of water across the membrane but rejects contaminates. In such a system the wastewater, or feed, is passed on one side of the membrane and an osmotic agent (OA), such as salt water, is passed on the other. The OA can use any solute as long as it can produce an osmotic pressure that is higher than that of the feed and the solute used is well rejected by the membrane.

The performance of FO as a water purification device along with other applications has been evaluated by many [5-16]. NASA has also tested FO for the treatment of space craft wastewater [5-9 &17-25]. NASA has a patent for the treatment of urine using a combined FO membrane bag with a granular activated charcoal (GAC) filter to pretreat the urine prior to introducing it into the FOB[18 & 26] . NASA has also used the FO principle in the Direct Osmotic Concentration (DOC) technology [5-8 & 23-25] and is currently developing it as a post treatment system through the Next Generation Life Support [NGLS] project. This OCT funded program is developing a version of it called the Forward Osmosis Secondary Treatment (FOST) system. NASA also has evaluated the us of the FO bag and for desalination during space craft water landings [20].

The FO bag used in the FO-CTB is based on the Hydration Technology Innovations (HTI) product called the X-Pack™. NASA has completed extensive testing of the X-Pack™[17-18, 20-22, & 27] This testing has shown that the X-Pack™ in combination with granular activated charcoal (GAC) is capable of rejecting ≥ 90 % of the salts, ≥ 85 % of the Total Oxidizable Carbon (TOC), ≥ 95 % of the Total Nitrogen (TN), and ≥ 93 % of Urea - Nitrogen (BUN) in urine while completely removing a mixed bacterial population of > 108 cells per milliliter of raw liquid. The X-Pack yields ≥ 0.9 L of liquid product from 1.0 L of raw water in 4-6 hours at 25°C. The membrane has a microbial disinfection capability of > 6 - log units (i.e. ,removing 99.9999 % of a bacterial population from raw water) and reduces the concentration of many commonly found environmental contaminants.

HDU Testing

A demonstration of a FO-CTB was completed at the August 2011 D-Rats HDU field demonstration project. The objective of this demonstration was to construct a FO-CTB bag that could be filled, drained, and would demonstrate its function as radiation protection and water recycling.

Methods

The FO-CTB was constructed from modified X-Pack™ like bags placed in pockets of a simulated cargo transfer bag constructed of canvas. The FO-CTB is shown in Figure 1 folded up in its cargo carrying form. 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). The size is derived from the current standard CTB size for the International Space Station.

The FO-CTB is designed to function like a standard CTB. It is folded into a rectangle and used to haul cargo. However, once the cargo is removed from the FO-CTB and the bag is unfolded it can be reused as a radiation protection water wall and for water purification. The unfolded FO-CTB is shown in Figures 2 and 3. Figure 3 shows unfolded bag with a FO bag plumbing array suspended in front of the CTB in the approximate location of the internal bags. The unfolding exposes 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. The internal plumbing of the FO bags is shown in Figure 4. Figure 5 shows an individual FO bag used in the FO-CTB.

Figure 1: Folded FO-CTB water wall architecture element demonstrator.

Two operational FO-CTB bags were constructed. One was tested externally of the HDU to demonstrate the ability to fill, process, and drain the FO-CTB and the other was installed in the HDU to demonstrate how a combined radiation shield water wall and FO treatment bag could be installed lining the inside of the habitat.

Figure 2: Two unfolded CTBs side by side

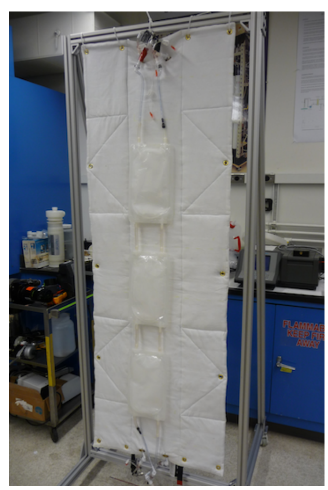

Figure 3: Unfolded FO-CTB water wall showing FO bags and plumbing.

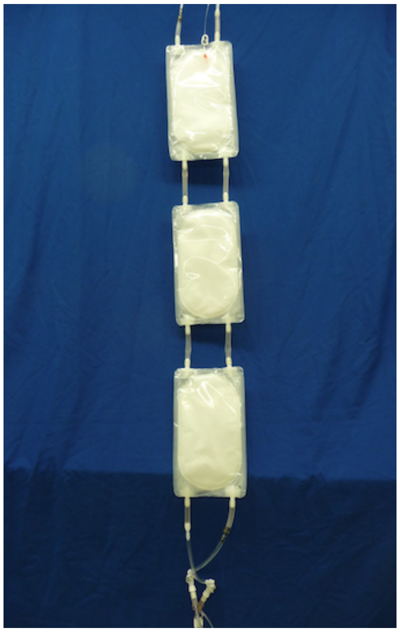

Figure 4: Testing of a three-bag array of FO bags prior to their insertion into the lining of a FO-CTB water wall Element.

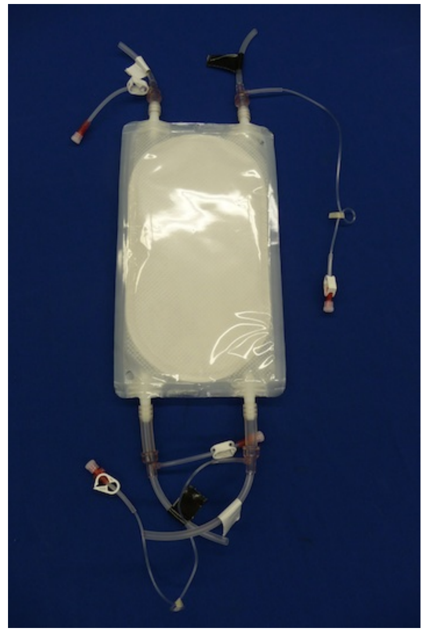

Figure 5: Individual four port bag used in FO-CTB bag design.

HDU Results

The placement of the FO-CTBs inside the HDU is shown in Figures 6 and 7. The FO-CTB was installed in the hygiene module behind a cabinet as shown in Figure 6. This Figure shows the FO-CTB is ideally suited for placement in the HDU structure. Figure 7 shows the detail of how it was attached to the inner support structure of the HDU. Also shown are the feed and product connectors. The ability to install the FO-CTB against the inner wall of the HDU demonstrates its use as internal radiation sheading.

The use of the CTB bags as radiation shielding was also demonstrated by installing them external to the HDU module. This is shown in Figure 8. In this approach the CTB placed on the external surface of the vehicle or habitat.

The second FO-CTB was tested externally to the HDU to demonstrate the ability fill, drain, and treat simulated wastewater. This FO-CTB was composed of a three-bag element (2 L each) as shown in Figure 4. This FO-CTB was tested using an NaCl salt water draw solution and a standard blue food coloring dye as simulated wastewater. This was a qualitative performance test designed to mirror the operational "in field" operational testing of the system.

During these tests 6 L of simulated wastewater was feed into the FO-CTB . Approximately 5.4 L of product was generated. The osmotic draw solution used was a 32 g/L NaCl solution and the product was the diluted osmotic draw solution. The effectiveness of the water treatment was evaluated by observing that no dye passed from the feed to the product. No chemical or biological analysis was performed.

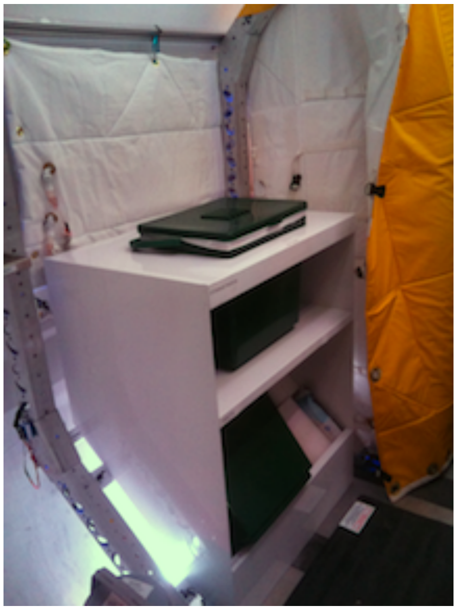

Figure 6: CTB water wall Architecture Demonstrator seen internally mounted in the D-RATs habitat demonstration unit August – September, 2011

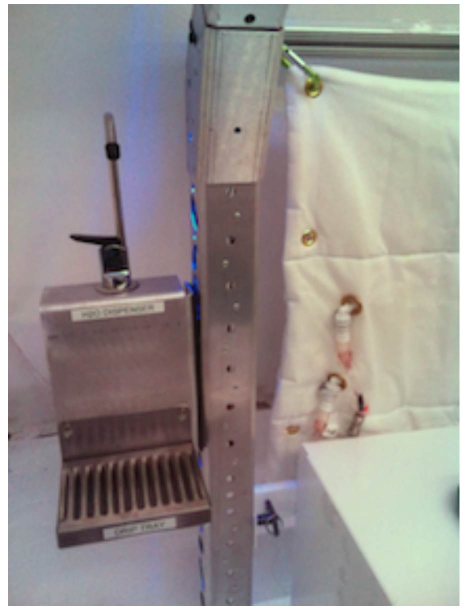

Figure 7: End close-up of CTB water wall architecture demonstrator seen internally mounted on the D-RATs habitat demonstration unit August – September, 2011

Figure 8: Exterior radiation sheading CTB mounting demonstration

Flight Testing

Microgravity flight testing was completed in 2011 onboard the STS-135 Atlantis Space Shuttle mission. The objectives of this flight experiment was to evaluate the performance of FO bags used in the FO-CTB in microgravity. It also verified procedures for filling and draining the bags, the effects of concentration polarization, and membrane wetting characteristics in microgravity [30].

Methods

A custom forward osmosis bag based on the design of the Hydration Technologies Innovation (HTI) X-Pack™ was developed for this application. This Forward Osmosis Bag (FOB) was fabricated by HTI under contract from Kennedy Space Center (KSC). It was modified from the X-Pack™ to have two quick disconnect connections to add and remove fluids in microgravity and the materials of construction were changed to a safety approved space flight qualified plastic. The original X-Pack outer shell is made out of polyvinyl chloride, whereas the FOB outer shell was fabricated out of polyethylene. Figures 9 and 10 show the commercially available X-Pack and the NASA flight FOB bag. Bags are dimensionally the same, approximately 12 inches by 7 inches.

Figure 9: Commercially available X-Pack™

Figure 10: Forward osmosis bag (FOB) flight design

The experiment occurred onboard the space shuttle (STS 135) after undocking from the International Space Station. A shuttle crewmember injected a preloaded mixture of a lower concentration liquid consisting of a 550ml potassium chloride solution with methyl blue dye into the outer chamber of the FOB. This dye containing mixture represented the "dirty" water. A higher concentrated "draw" solution, containing a 60 ml sugar solution with fluorescein dye, was then injected into the bag's inner chamber. A total of six bags were tested. Three were left undisturbed during the experiment while the crewmember hand kneaded the remaining three bags at the start of the experiment to assist in the mixing of the fluids. Figure 9 shows the components used in the filling and draining procedure. Figure 10 shows the complete assembly on orbit.

Figure 9: FOB Experimental Components

Figure 10: FOB Filling in Flight

After six hours of stowage, the crew utilized sample syringes to connect to the inner chambers of each bag and remove 60 milliliters of the draw solution from each of the six bags and then stowed them for landing. The reduction in fluorescein of these samples was used with a standard curve to calculate flux. In addition, once the FOBs were returned to Earth a post-flight analysis of the product remaining in the bag was completed.

Flight Results

Results of this experiment demonstrated that the FO process functions in microgravity. Specific ion rejection rates were the same as measured during ground testing. Flux rates were reduced in microgravity by up to 50%. The flux data had a significant scatter. Ground based testing indicates this error is due primarily to the materials of construction of the FOB. In addition, the florescent dye used was also subject to photo bleaching in the ground tests and also contributed to the observed scatter in the data. As a result the exact amount of flux reduction in microgravity remains to be determined. [28]

The syringe pump approach for both feed introduction and product removal was shown to work in microgravity. The crew had no reported operational problems using the system. Results also demonstrated that there was no statistically significant difference between the flux rate in the mixed and unmixed bags. [28]

Significant fluid wicking occurred during the filling process as shown in Figure 10. This is not characteristic in a 1 g environment. Although this wicking did not impede full fluid coverage in the flight experiment it could be a problem if less than a full bag of feed is used. [28]

Future Work

HDU

A next generation FO-CTB is currently being developed for testing in the 2012 HDU. Plans are to test the FO-CTB with hygiene water generated in the HDU and demonstrate the treatment of hygiene water into a fortified potable drink similar to Gatorade™ or Country Time Lemonade™. The product will be analyzed to determine if it meets potable or food grade standards but will not be consumed by the crew.

The CTB design used in the FT 12 FO-CTB will be updated to reflect the latest L2L CTB bag design. This new CTB has been redesigned to facilitate unfolding into a flat sheet. A picture of this new bag design is shown in Figure 7 and Figure 8. The CTB shown in these figures was a prototype configuration and the final bag will be modified to place the zipper on the right side panel. This is being done to maximize the usable uninterrupted usable surface area of the bag.

The next generation FO-CTB is also currently being designed as of the writing of this paper. One concept currently being pursued is the construction of a completely integrated FO bag system. In this configuration the FO membrane and plastic outer liner would extend over the entire surface of the CTB. All plumbing connections would be integrated into the glue/seam pattern used to construct the FO membrane array. Figure 9 shows the laminate cross-section of the proposed FO-CTB. This configuration is designed to use two FO-CTB flipped and laying over another and slightly offset so that the seams of one bag are covered by the water bladders of the second to provide radiation shielding.

Figure 7: New L2L CTB folded in cargo containing configuration.

Figure 8: New L2L CTB unfolded in reuse configuration.

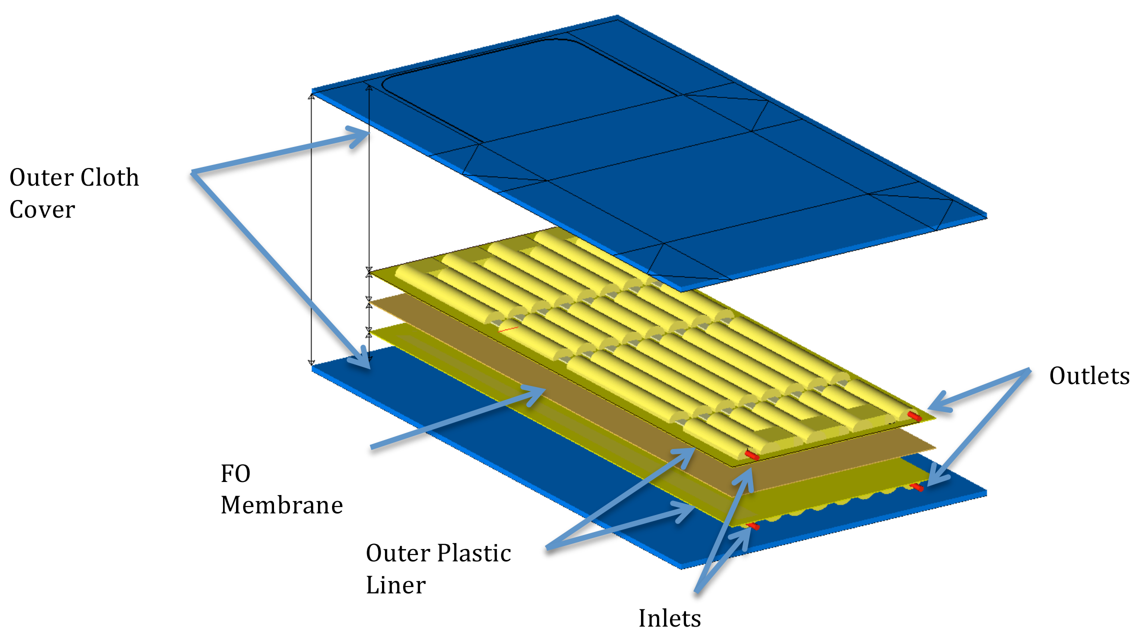

Figure 9: Exploded view of proposed new FO-CTB design with internal water bladders filled. Bladders lay flat in unfilled bags.

Flight

Future flight opportunities are being pursued. Two Detailed Test Objective (DTO) flight opportunities currently exist. The FO-CTB bag is currently under consideration for a NASA directed test objective (DTO) mission some time after 2013. The objective of this test is to demonstrate filling and draining the FO-CTB in microgravity. It is expected that a series of these flight qualified FO-CTB bags could provide microgravity flight demonstrations of individual technologies such as water, air, and waste recycling, thermal control, radiation shielding and in situ structural element development. The first FO-CTB DTO is designated JSC-100.

The second flight testing program will focus on re-flying the FOB to fully quantify microgravity performance. This flight will differ from the first flight in that the FOB will be remanufactured out of a more suitable outer bag material and a non-photo bleaching florescent dye. These flights are scheduled to fly as a DTO payload sometime after 2013. This DTO is designated JSC-95.

Conclusions

This paper discusses the reuse of the CTBs to provide multiple functions such as radiation protection, life support capacity in addition to their primary use as cargo transfer bags. This work is being pursued to evaluate if reuse of these CTBs will reduce the logistics required to support ISS.

The LTL concept redesigns CTBs to enable disassembly on-orbit (unfolding). The deconstructed CTBs are then filled with water and reused for radiation shielding and life support functions. These CTBs are modified to include a inner bladder that allows them to be filled with water. The CTB can then be used as a radiation protection water wall. In addition, if the CTB bladder includes of a forward osmosis (FO) membrane the CTBs can then be used to recycle wastewater.

A prototype FO-CTB was tested this August 2011 in the D-Rats HDU field demonstration project. This testing demonstrated FO water recycling bags integrated into a CTB simulator. The primary objectives to construct the CTB, integrate it within the HDU, and demonstrate basic function as a water treatment system were achieved. Future testing will further develop the FO-CTB concept into the fit form and function of a flight system.

A flight test of a stand-alone FO bag, the functional element of the FO-CTB, was completed as a sortie payload aboard the STS-135 Shuttle Mission, STS-135 in early July, 2011. This mission tested a flight qualified version of the FO bags used in the FO-CTB. The flight version of the bag is called the Forward Osmosis Bag (FOB). This testing demonstrated that FO works in microgravity but flux rates were reduced. Future flight test will be required to fully quantify this reduction in performance.

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