Dual Use of Packaging on the Moon: Logistics-2-Living

A. Scott Howe, PhD[1]
Robert Howard, PhD[2]
NASA Lunar Surface Systems Project (LSSP) Habitation Team members[3]

This paper describes a modular packaging system for logistics that can be reconfigured into internal outfitting for a lunar outpost, including desks, chairs, partitions, cabinets, and radiation shielding. Logistics include clothes, equipment, food, and other consumables needed to sustain the crew for the duration of the mission. A significant mass penalty is required for the packaging and handling of logistics for re-supply of short to long-term space missions that must be brought out of the gravity well on a launch vehicle. Once the supplies have been exhausted, the packaging material is typically of no further use and is discarded. If a scheme can be developed that reuses the logistics packaging, the mass penalty can be reduced.

In this research, a modular packaging system has been devised as a kit-of-parts that can be used for both handling logistics supplies, and then reconfigured into desks, chairs, partitions, cabinets, and radiation shielding. The system is derived from a standard International Space Station (ISS)-type Cargo Transfer Bag (CTB), using soft, unfoldable box-like containers with stiff metal inserts. The empty hydrogen-impregnated CTBs can be used as-is for cabinets, opened up for use as partitions, or draped over the habitat as layers of radiation shielding. Stiff metal inserts can be reconfigured into desks and other useful outfitting.

As part of the investigation, the kit-of-parts was used to convert a stack of launch configuration CTBs into a geo-science workstation, complete with functioning glove box, tools, and video imaging. The conversion exercise was performed in a Microhab habitat analog at the NASA Desert Research and Technology Study (D-RATS) field tests in Arizona.

Significant findings include a greater understanding of habitat internal mounting schemes, component configurations, folding techniques, fasteners, and reconfiguration procedures.

Key words: logistics packaging, internal outfitting, recycle and reuse, kit-of-parts

I. Introduction

ONE of the most critical constraints in space system design is mass, because of the high costs of lifting every kilogram of payload out of the earth's gravity well. It then becomes the responsibility of the design team to lighten the mass of the spacecraft as much as possible to ensure requirements are satisfied and objectives are met within the mass budget constraints.

This is also true for habitation systems, where consumables and logistics required to maintain a habitable environment for the crew must carefully be bookkept and accounted for in a timely manner in any sequence of flight manifests. Habitable flight systems have a more difficult problem, because frequently insufficient consideration is given for mission logistics mass. Also, every kilogram of supplies require some amount of packaging that may end up as refuse after the product is consumed. Therefore the problem is not only how much packaging is needed for a mission, but how much trash and refuse is generated as well.

Since logistics packaging cannot be designed away, the options left to the designer are to lighten the system as much as possible, and provide for additional uses beyond the original packaging function. In this exercise we have

[1] Jet Propulsion Laboratory, Calif Institute of Technology, 4800 Oak Grove Dr, M/S 301-165, Pasadena, CA 91109
[2] NASA Johnson Space Center, 2101 Nasa Parkway, Houston, TX 77058
[3] NASA Lunar Surface Systems Project Habitation Team members involved in the Logistics-2-Living study include: Larry Toups (LSSP Habitation Lead), Kriss Kennedy, Brand Griffin, Robert Howard, Scott Howe, Evan Twyford, Jason Poffenburger, and students Rainer Zierer, Tim Huntzinger, and David Orme.

explored the possibility of reducing trash in the end by making the packaging material useful even after the original purpose has been filled. By requiring all packaging systems be dual-use, we will be able to reduce the mass that needs to be lifted out of earth's gravity well for human spaceflight missions.

Space architects have defined three classes of planetary surface construction – Class I as pre-integrated, ready to use structures, limited by payload size and volume; Class II as pre-fabricated, using kit-of-parts systems assembled in-situ, and not limited in size or volume but by the number of payload manifests; and Class III as In-Situ Resource Utilization (ISRU-derived) structures that use native materials (Kennedy 2009). Our concept for dual use of packaging materials designs the packaging system as a kit-of-parts that can be reconfigured and assembled later into other structures, falling within a Class II structure system. The kit-of-parts can be assembled into reconfigurable interior partitions, cabinets, desks, and other furniture to save mass on outfitting required for habitability. In addition, crews can use discarded logistics containers to fill with regolith and stack like bricks to make walls and other structures.

II. Logistics Systems

The International Space Station (ISS) logistics system is comprised of three major elements: (1) soft stowage bags, (2) hard frames to resist launch loads, and (3) attachment points for mounting the system (Figure 1). The smallest increment of size for the bags are 50.2cm x 42.5cm x 24.8cm, which is a convenient size for one person to handle and carry around (Figure 2). Multiples of the basic bag are often combined in larger bags for 4, 6, and 10 CTBs to help organize the supplies.

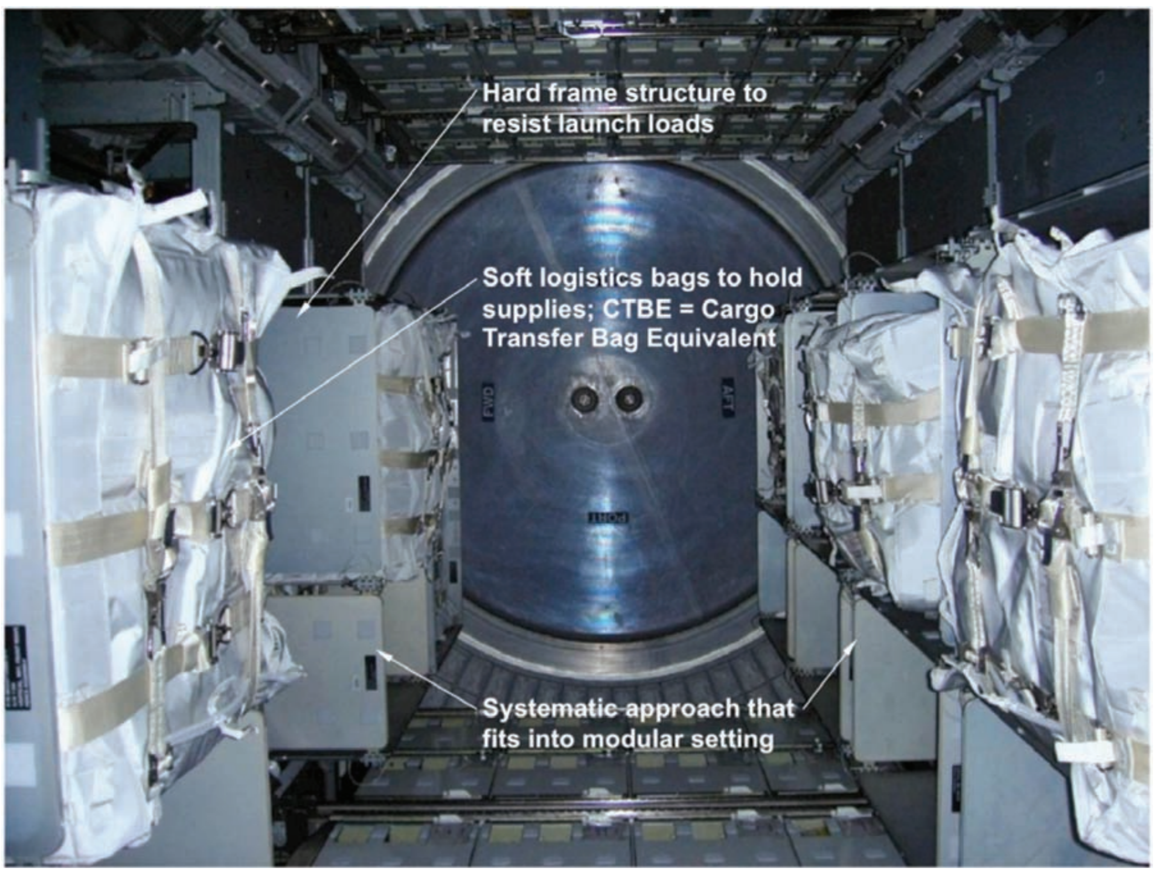

Figure 1: International Space Station (ISS) logistics packaging (courtesy of NASA)

For a particular mission, the required pressurized logistics are organized into CTB increments and manifested on a flight by flight basis depending on the mass or volume allocations. Logistics are inventoried, with the contents of each bag known and the bag's location known. When planning logistics packaging locations inside a pressure vessel module, it may be possible to plan for a sequential access from one end to the other, where the crew pulls one bag out which has everything they need for the day, slowly 'eating their way' through to the interior. This method would allow for higher densities of packaging, but unfortunately in practical terms it would doom the crew to not have access to the items deep inside the module, even in an emergency. Therefore, by rule all logistics bags must be accessible in random access fashion at any given moment. This requires corridors or access routes with a lower overall packed density, but will be safer for the crew (Figure 3).

With packaging a given, the designer needs to understand the causal path of that material. For example, our team determined that a mission of 28 days will require approximately 510kg of crew goods for four persons. We calculate 2kg for every 13kg of crew goods, so the 28 day mission would require approximately 78kg of packaging. If all of that packaging becomes trash, then 78kg of the mass budget would be taken up by useless materials.

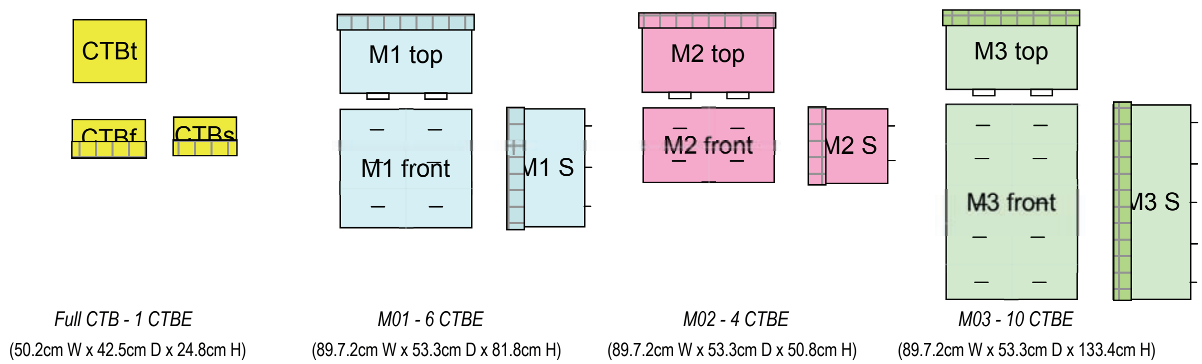

Figure 2: Cargo Transfer Bags (CTB or CTBE) sizes and multiples (prepared by NASA LSSP logistics team)

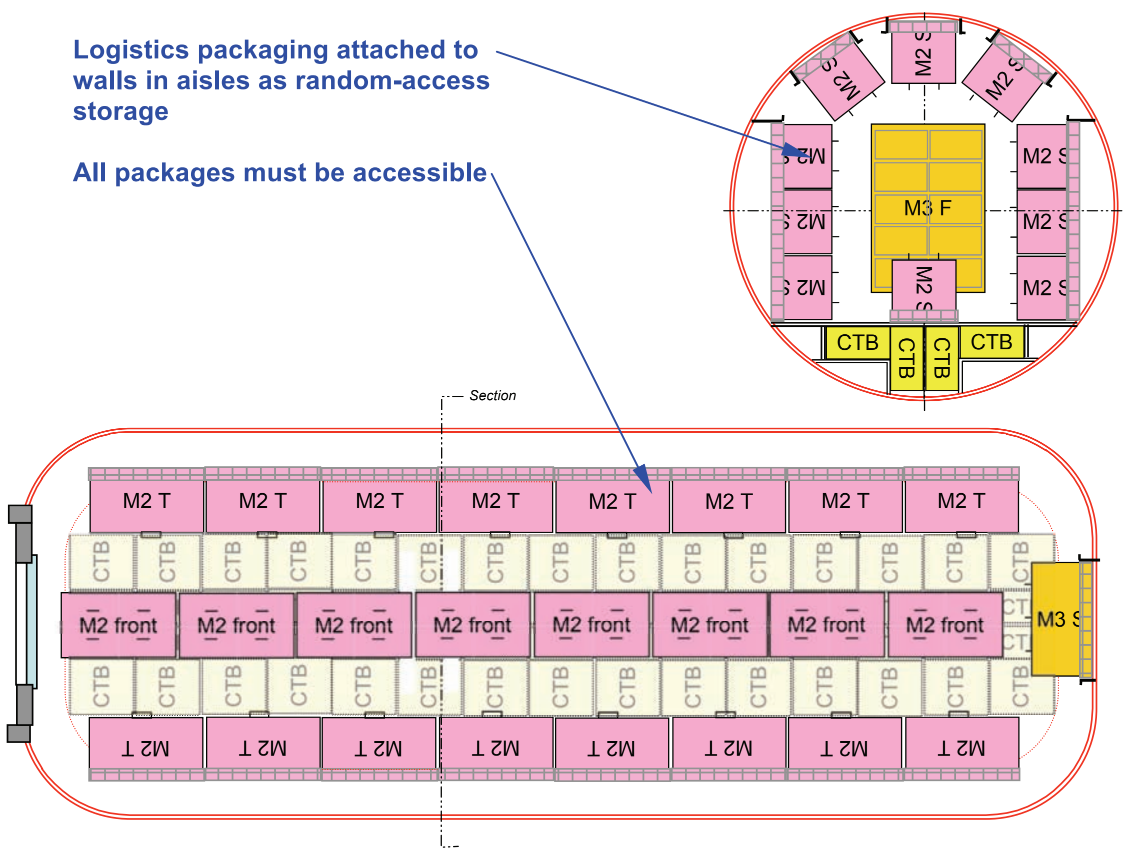

Figure 3: diagram showing dense packing of CTBs in cylindrical habitat

On the other hand, if we were to create a kit-of-parts system out of the packaging that actually contributes to the mission later on, 78kg could be saved as useful mass. The Logistics-2-Living concept converts both packaging material and stowed volume and converts it over to interior outfitting and living volume incrementally as the CTB bags are opened and the contents are consumed (Figure 4).

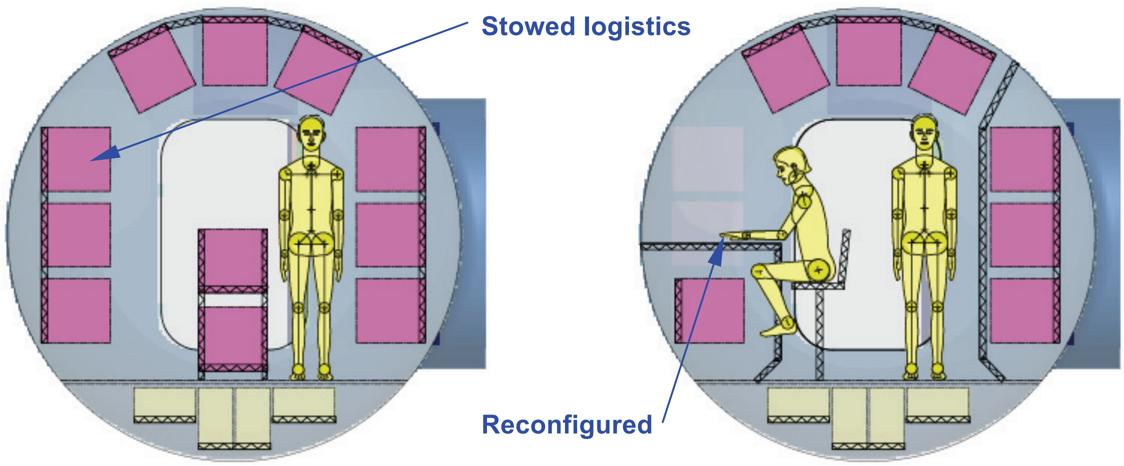

Figure 4: logistics packaging (left), can be reused as construction material for furniture and outfitting

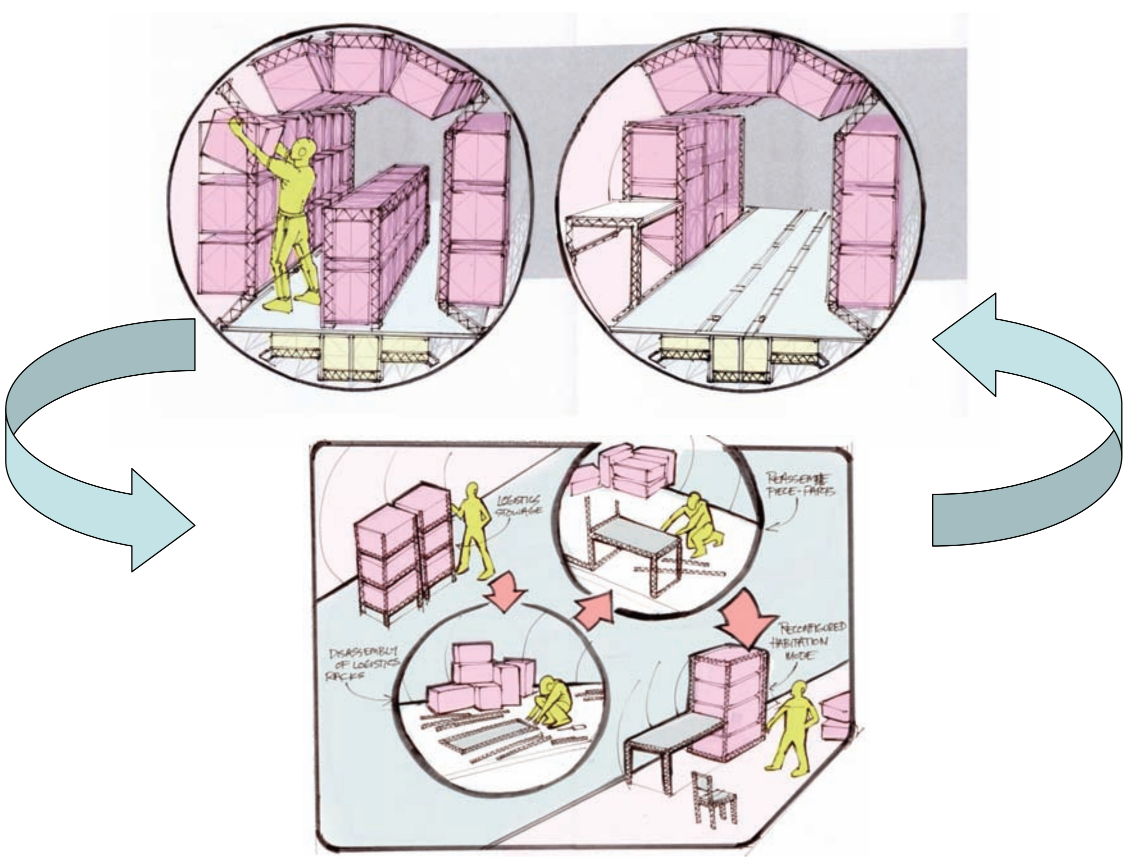

Figure 5: Logistics-2-Living concept -- logistics packaging becomes a kit-of-parts for furniture

Depending on the mission, hundreds of CTBs may be required. The kit-of-parts must not only be able to accommodate all the needs for interior outfitting (Figure 5), but also consider additional uses once the outfitting has been saturated. Some of the additional uses may require advanced thinking about how to design the bags, and the material they are made of. For example, one possibility is to construct the bags out of hydrogen-impregnated materials so that when the bag is opened up flat, it can be draped on top of the habitat or hung in layers to help with radiation protection.

III. Microhab Mobile Testbed

The NASA Lunar Surface Systems (LSSP) Habitation Team has gone through several exercises to gain a greater understanding of how a Logistics-2-Living (L2L) system might be designed. In addition to numerous paper studies, several physical prototype systems have been devised that will give the team greater fidelity of product by degrees. The first system was devised to work in partnership with the LSSP Mobility Team, using a scale habitat mockup called the 'Microhab', that is designed to be payload on the top of the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system (Figure 6). The ATHLETE consists of two three-limbed Tri-ATHLETE vehicles that can dock to either side of a payload for lifting and placing at specified locations.

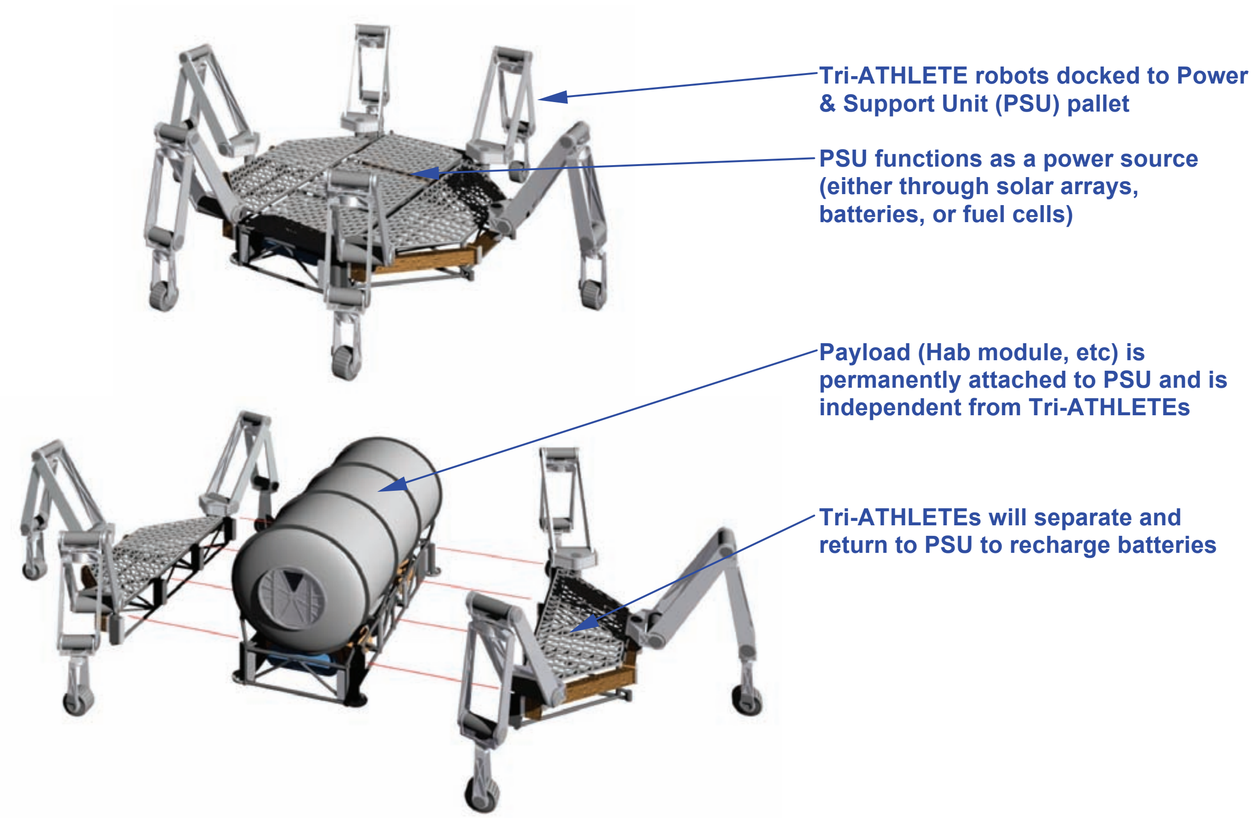

Figure 6: Habitat carried by ATHLETE mobility system

The heavy lift capacity of the ATHLETE was designed to carry large payloads, including habitation modules, from place to place on the lunar surface. ATHLETE is part of a robotic suite of vehicles for a projected lunar outpost, where all the outpost assets are highly mobile. A pair of Microhabs were manufactured as payloads for two ATHLETE vehicles to practice docking and payload carrying procedures. Simulated missions include two ATHLETE / Microhab pairs landing at different locations on the lunar surface, whereupon they must go and find each other remotely and dock up. Figure 7 shows field tests of docking performed at Moses Lake, Washington in 2008.

The Microhab interior was too small to perform habitability simulations, but was sufficient as a testbed for Logistics-2-Living research. One Microhab can represent a habitat module, where the other represents a logistics module delivered by ATHLETE. The Microhab is 12 feet long by nearly 8 feet in diameter, and for the purposes of the L2L conversion exercises a lightweight aluminum frame was installed to provide mounting points for both stowed cargo and converted outfitting and furniture (Figure 8).

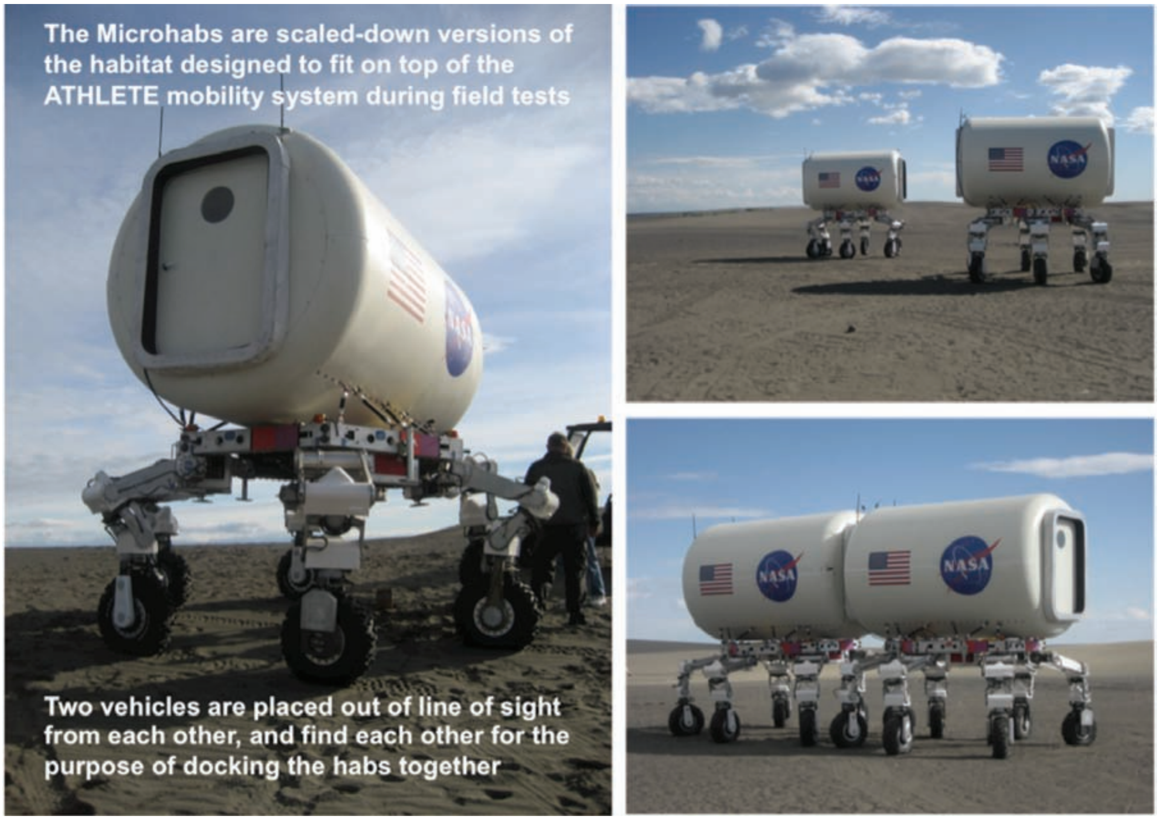

Figure 7: Microhab designed as a payload for ATHLETE

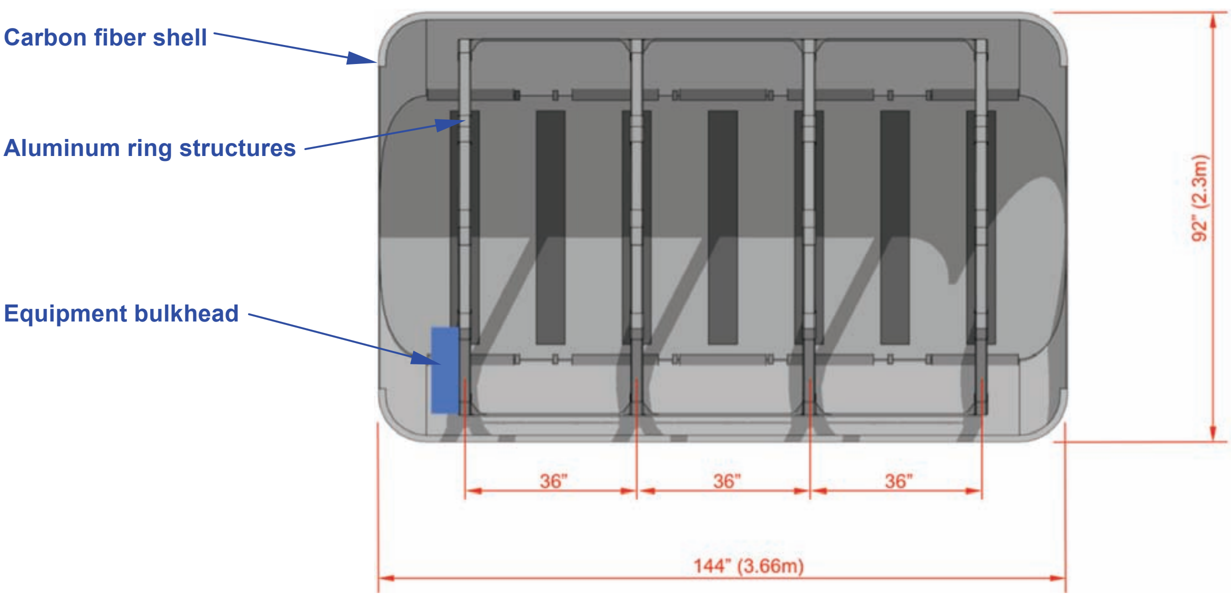

Figure 8: Microhab floor plan showing aluminum ring structures

The aluminum ring structures though extremely lightweight were designed with modular holes in increments that would allow the connection of common commercial off-the-shelf 80/20^{TM} connectors, plates, and components as well as a variety of other attachments (Figure 9).

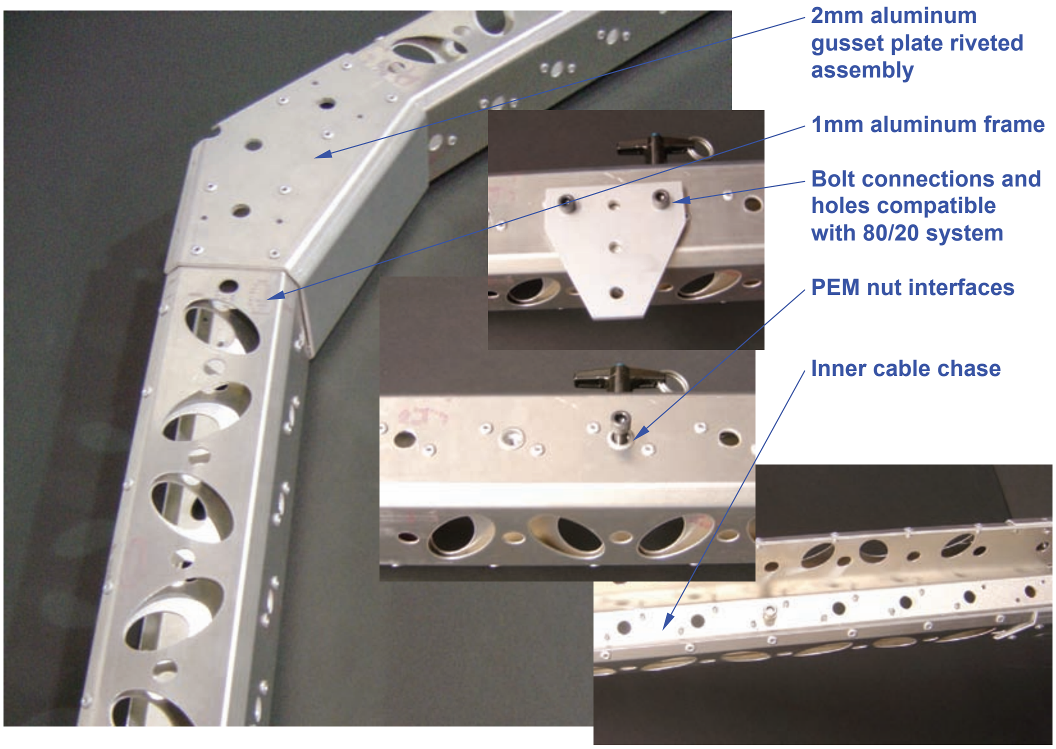

Figure 9: lightweight aluminum ring structures for mounting logistics

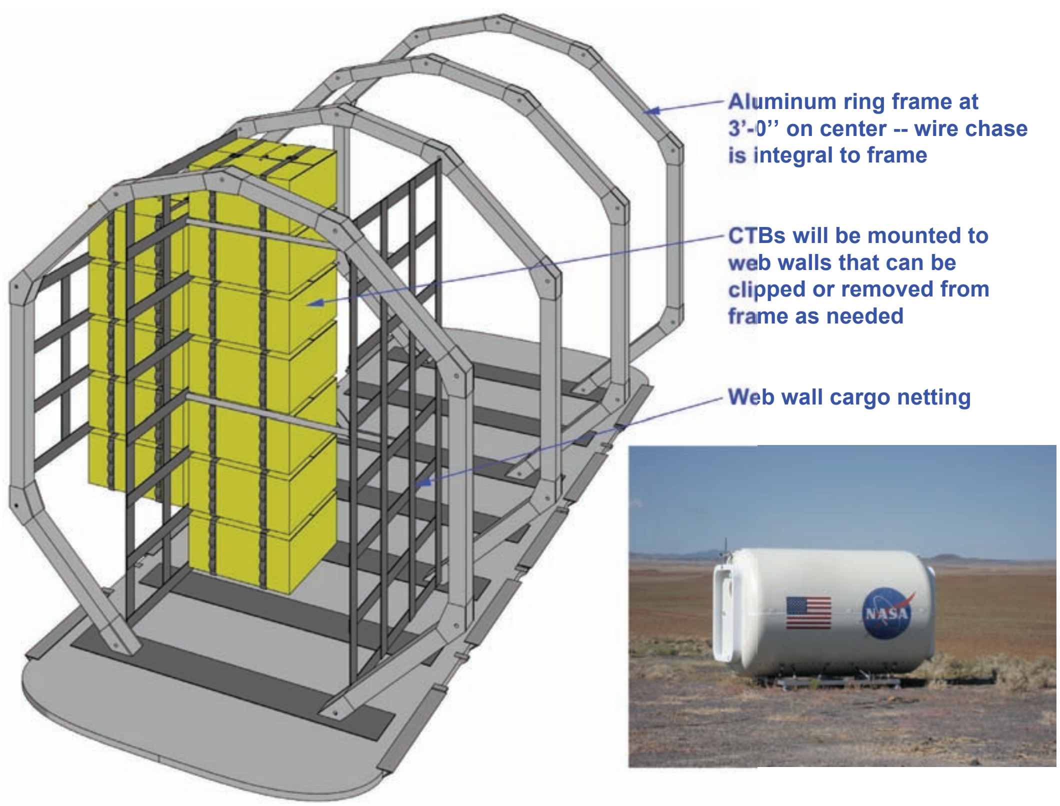

Figure 10: proposed logistics packaging in Microhab test article

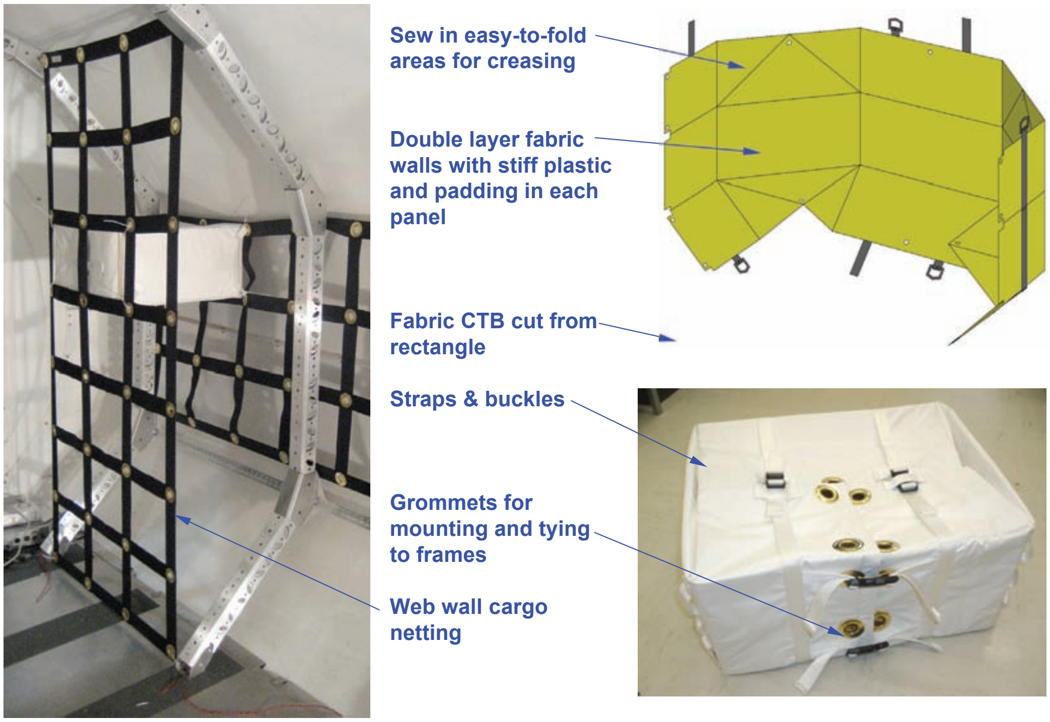

Figure 11: logistics packages can be unfolded into a rectangle and combined into other purposes

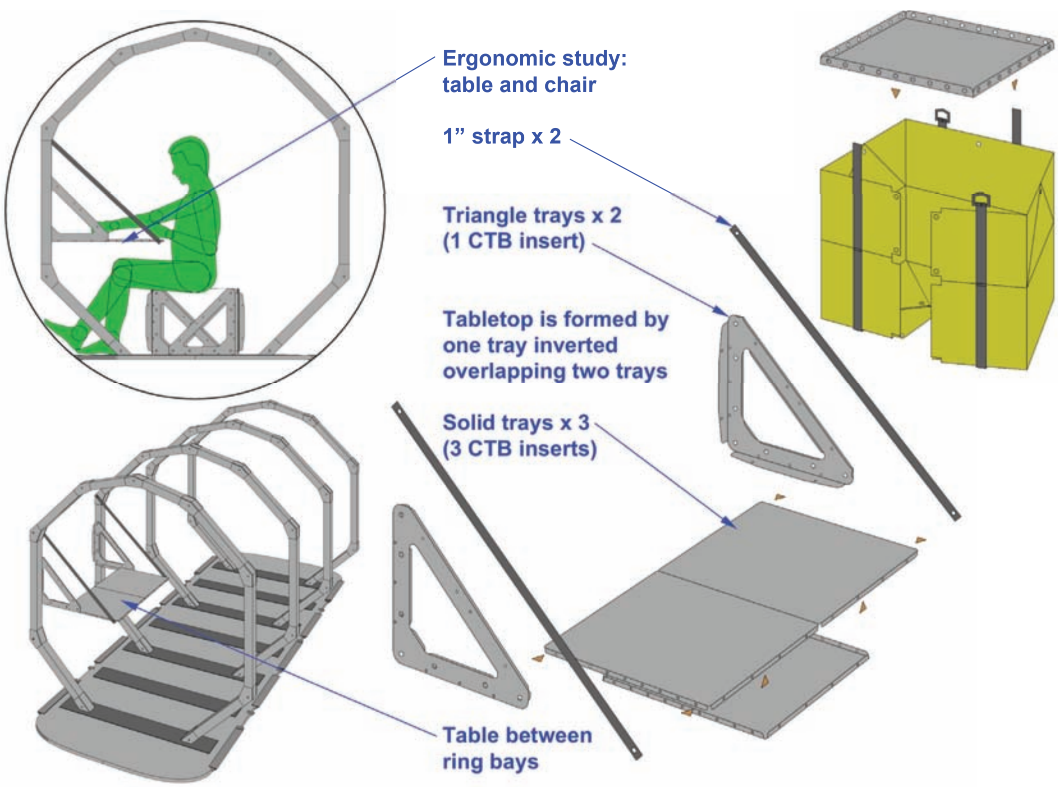

Figure 12: hard inserts function as compressive elements of furniture, as in this logistics packaging-derived table

In profile the aluminum frames were hexagonal shaped, based on an ergonomic 18” grid. The grid was designed to accommodate both the incremental size of the CTB for stacking and stowage, and for ergonomic mounting of tables, chairs, bunks, etc.

A. Logistics-2-Living L2L2009 System

By means of a ‘product code’, we would like to distinguish the Logistics-2-Living system described in this article as L2L2009, since later generations of L2L systems will evolve and develop. The L2L2009 CTB system uses the same dimensions as that used in the ISS logistics system, with 16.75” x 19.75” x 9.75” bags. In addition, a cargo net wall was used as an additional element in the system (Figure 10). CTBs could be stowed between cargo net walls (Figure 11, left).

In order to maintain structural rigidity to the bags and resist launch loads, the L2L2009 system uses two types of stiffener parts – an aluminum flat tray that fills the bottom of the folded box, and a pair of triangles that nest together and also fill the bottom of a box. Figure 12 shows how a combination of flat trays and triangles can be reused to create a table or desk by mounting the assembly to the Microhab aluminum ring frames.

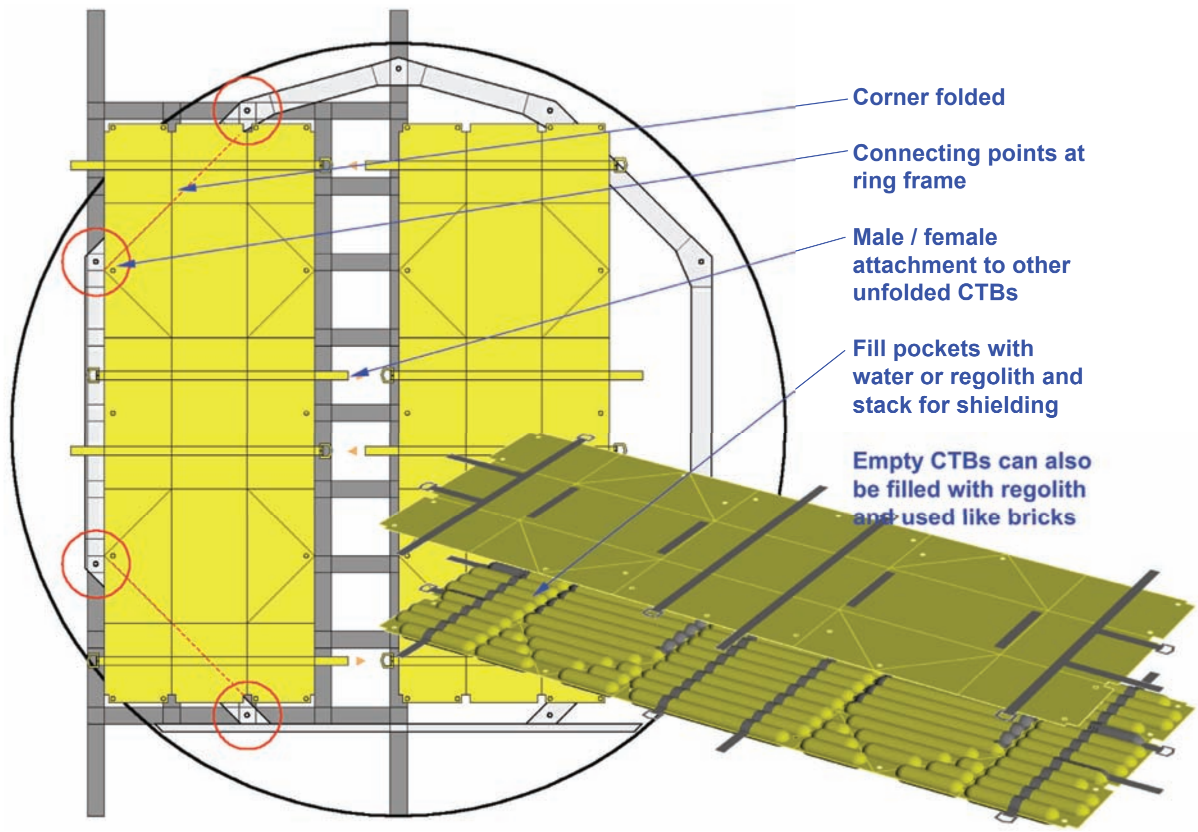

Figure 13: unfolded packaging can function as partitions and radiation shielding

The kit-of-parts CTB, though shaped similar to the ISS bags, was designed to unfold and become a rectangle with pre-positioned straps and grommets to allow attachment to each other. The unfolded rectangle is a little over six feet long and about 26 inches wide, shaped ergonomically for a variety of purposes. The rectangles have been fitted with grommets that coincide with the Microhab aluminum ring structure mounting points, to allow attachment as partitions (Figure 13). Other proposed features of the rectangles included hydrogen-impregnated materials that give the panel a radiation shielding attribute, that doubles and triples as layers are added. These layers can be draped across a habitat as hundreds of CTBs complete their usefulness as logistics stowage containers. Similarly, a double-walled version of the rectangle has also been proposed that can be filled with water for both water storage and water wall radiation protection, hung as panels or partitions (Figure 13, lower right). A third proposal was to manufacture the rectangles with flexible photovoltaic sections, so that the empty CTB could be used to lay across the ground outside and increase the power-generation capacity of the outpost.

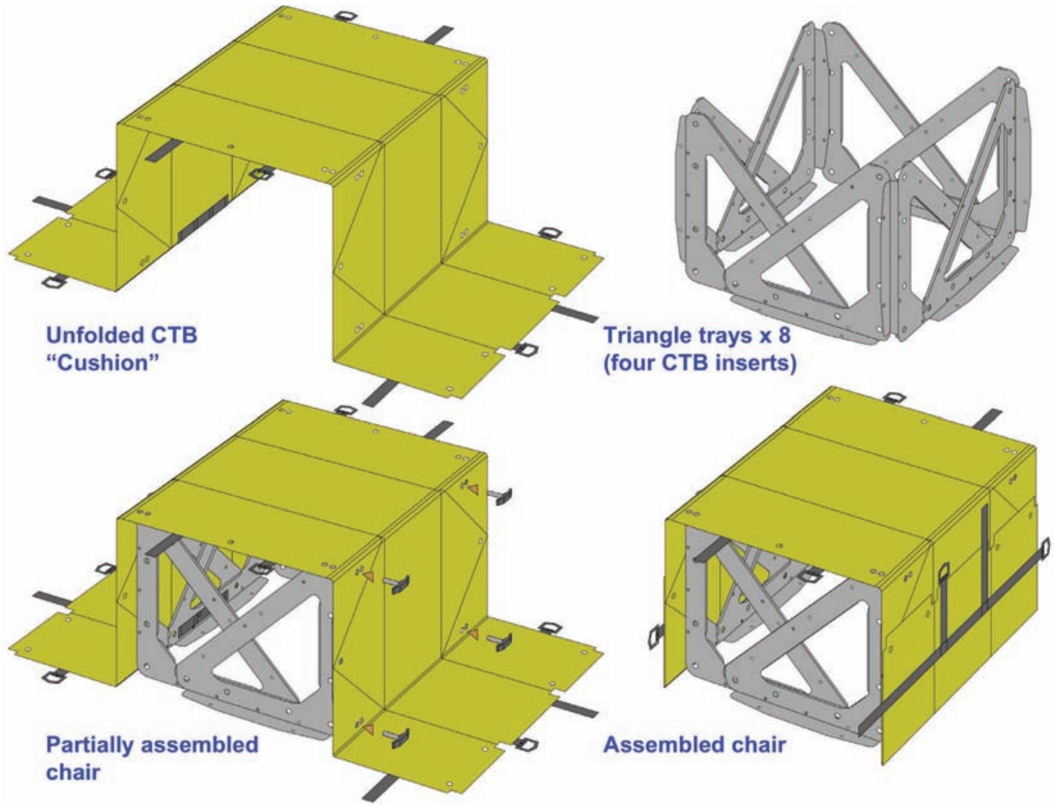

Figure 14: Logistics-2-Living chair design

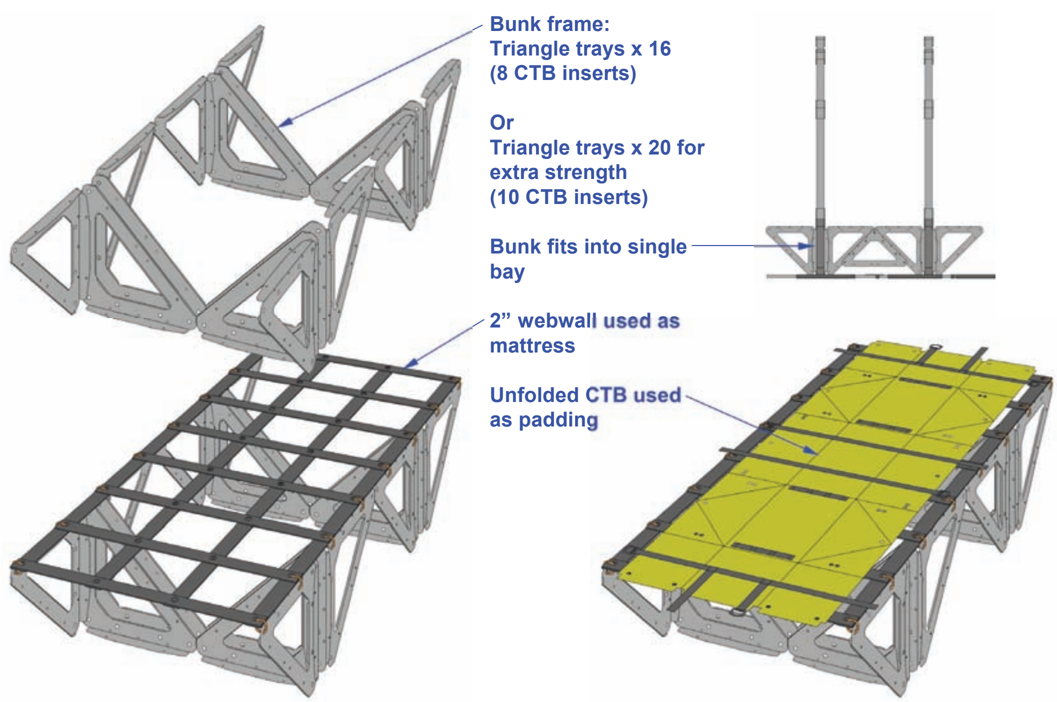

Figure 15: Logistics-2-Living bunk design

Other uses for interior outfitting include designs for a chair (Figure 14) and a bunk (Figure 15) that use combinations of hard inserts and unfolded CTB bags. The designs shown here were not as successful, but provided many lessons learned for future system design.

It has also been proposed to use expended CTBs external to the outpost as bricks for in-situ structures. Empty CTBs would be filled with regolith and piled in alternating courses on either side of a habitat module for radiation protection. CTB bags would function similar to sandbags, and could be used for all sorts of civil engineering works including berms, walls, strengthening trenches, and even paving.

B. D-RATS 2009 Field Tests

The Microhab mobile test platform along with the L2L2009 Logistics-2-Living system was tested at the 2009 Desert Research and Technology Studies (D-RATS) field test. The Microhab was fitted with thirteen L2L2009 CTBs to simulate a launch configuration. Figure 16 shows the internal launch packaging during a dry run at the Jet Propulsion Laboratory (left), and the actual field test at D-RATS 2009 Black Point Lava Flow in Arizona (right). Of the thirteen, six of the CTBs were used as mockups (three each stacked on either side in Figure 16) of yet-to-be-used logistics, and the seven CTBs stacked in the middle were packed with all the equipment needed to convert into a geo-science workstation, complete with glove box, laptop, cutting and analysis tools, and electronic imaging equipment.

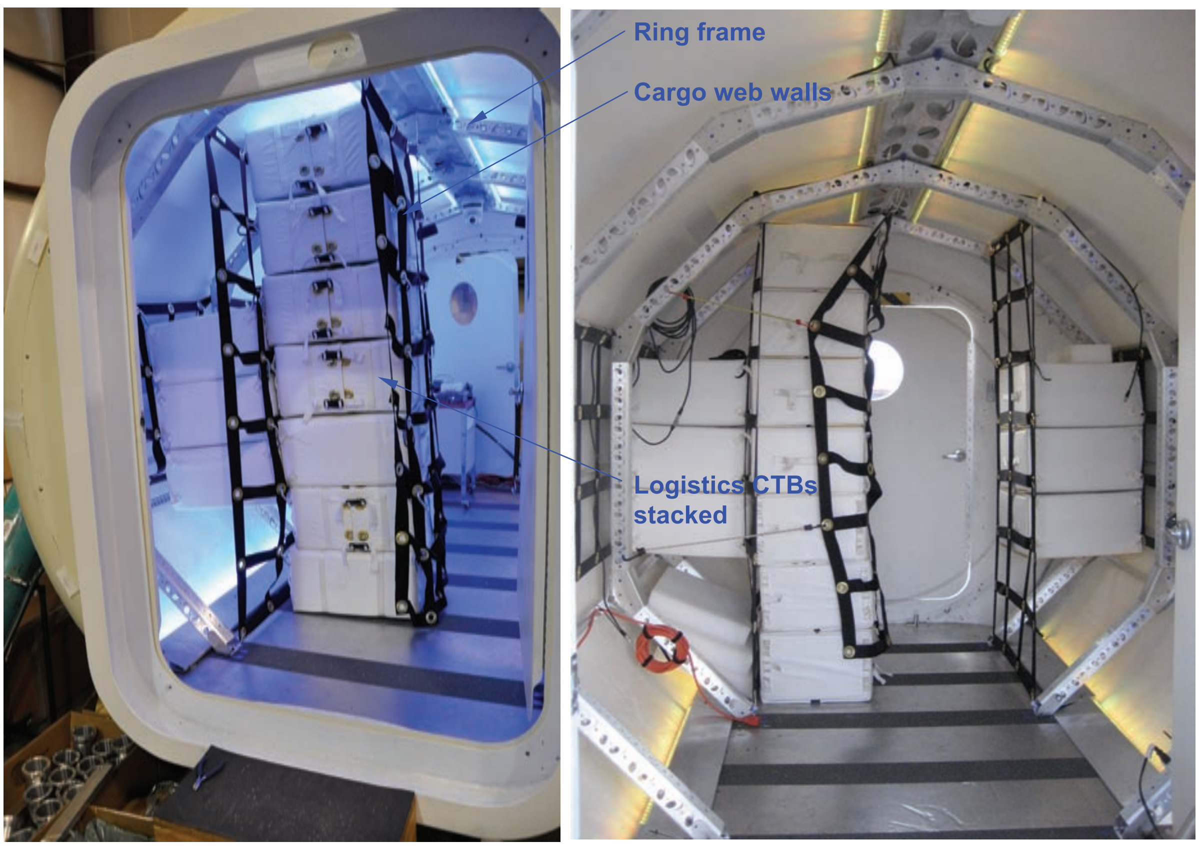

Figure 16: logistics packaging stacked and ready for use and reconfigure

An inventory of the seven CTBs was created, listing the contents of each bag. In addition, a set of procedures for assembling the geo-science workstation was generated. At the D-RATS 2009 field test, several test teams were conscripted to assemble and disassemble the packages into the workstation. Early teams helped generate the procedure list through their step-by-step process, and later teams followed the procedures with little or no outside assistance. Figure 17 shows a screen capture of the Microhab's internal remote control camera as an astronaut crew member begins to unload CTBs (left) and assemble the workstation according to the procedures (right). **Figure 18** shows unpacking of geology instruments (left) and assembly and test of the glove box (right).

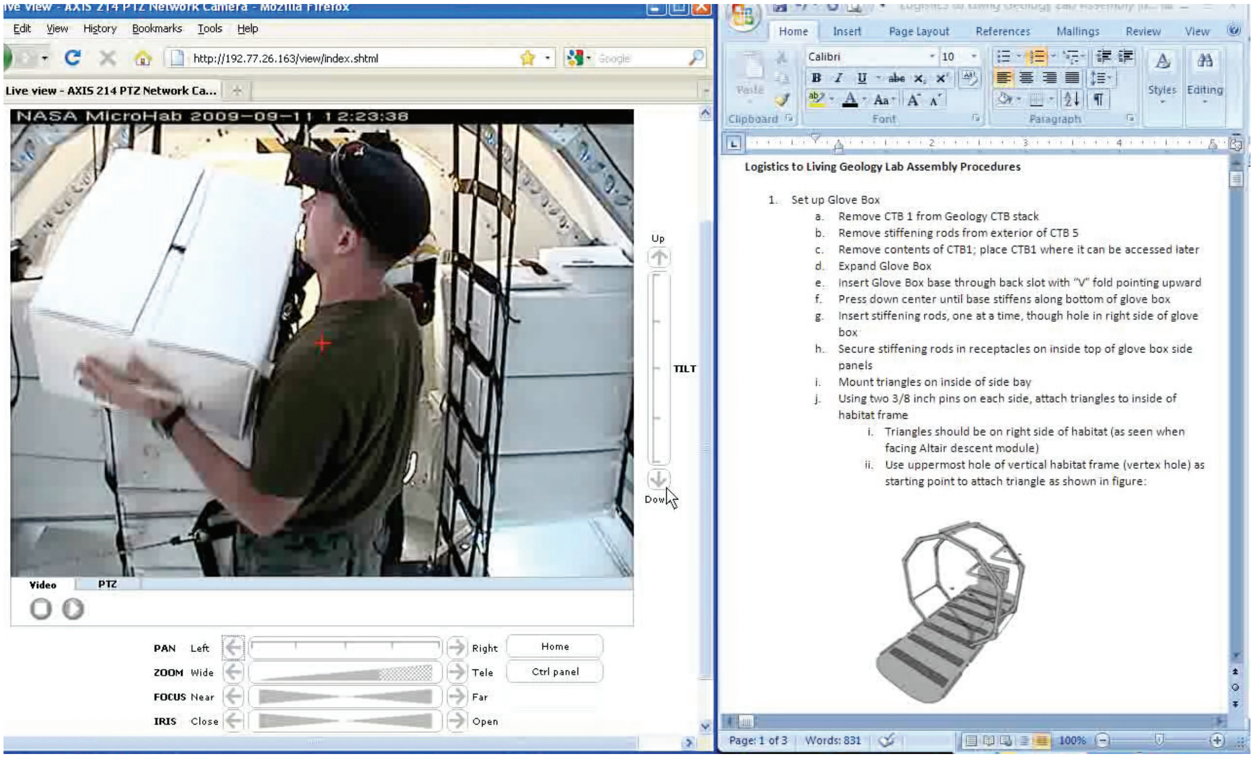

Figure 17: procedures were created (right), that were followed by the astronaut crew member (left), and captured via real-time video camera

Figure 18: astronaut crew member assembling geoscience workstation from logistics packaging – unpacking of science instruments (left), and adjustment of glove box (right)

Partitions, doors (Figure 19), and furniture were assembled using a variety of fasteners, including rivets, pins, plastic zip-ties, carabiners, and bolts. The more successful fasteners such as pins were easily removed and used over and over again, whereas the one-off fasteners such as plastic rivets and zip-ties sometimes had to be cut and removed, creating additional waste.

Figure 20 shows the final geo-science workstation as reconfigured from the L2L2009 system. The workstation spanned the aisle of the Microhab, using one of the 3 foot-wide bays defined by the Microhab aluminum ring frames. On the left of Figure 20, the glove box was installed on top, with two CTBs used as storage cabinets underneath. The glove box was equipped with cutting and analysis tools, mini cameras and imaging systems, and sample containers. On the right of Figure 20 across the aisle of the glove box was a counter top with two additional

CTBs installed as storage cabinets underneath. The laptop was set up to view and record video imagery captured by the mini cameras in the glove box, with wiring strung through the wire chase of the Microhab aluminum ring frame.

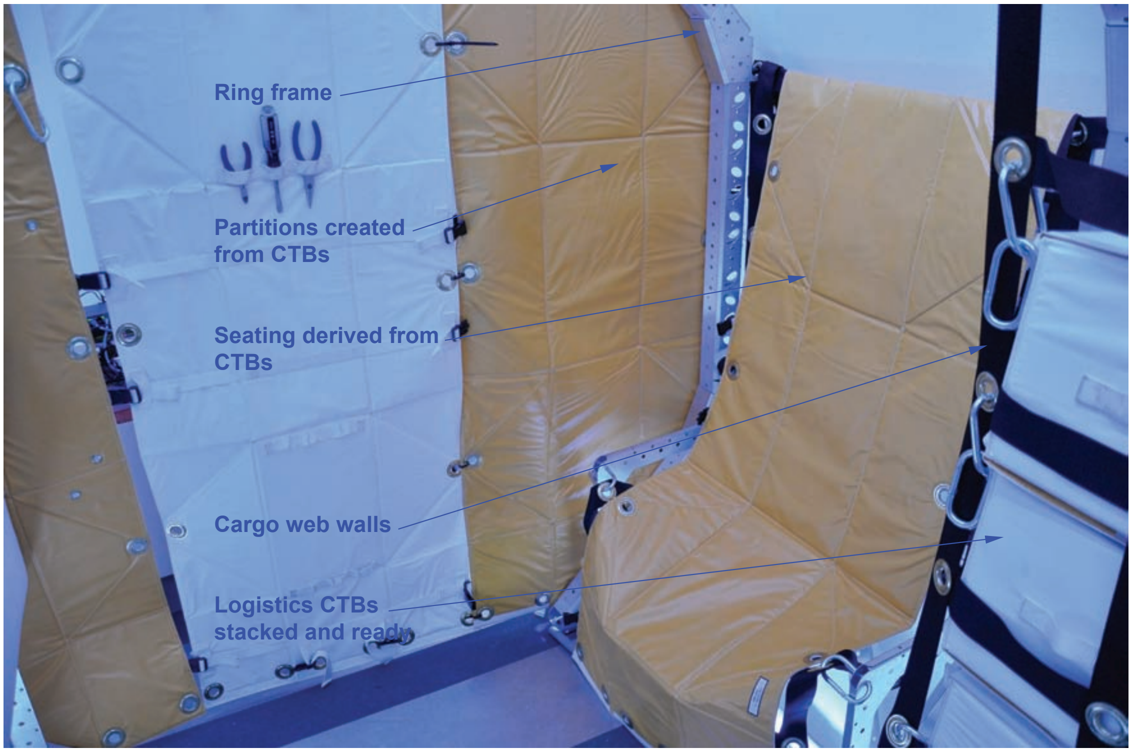

Figure 19: partitions and interior outfitting assembled using logistics packaging – seating (right) inspired by CalPoly San Luis Obispo students under Professor Donna Duerk

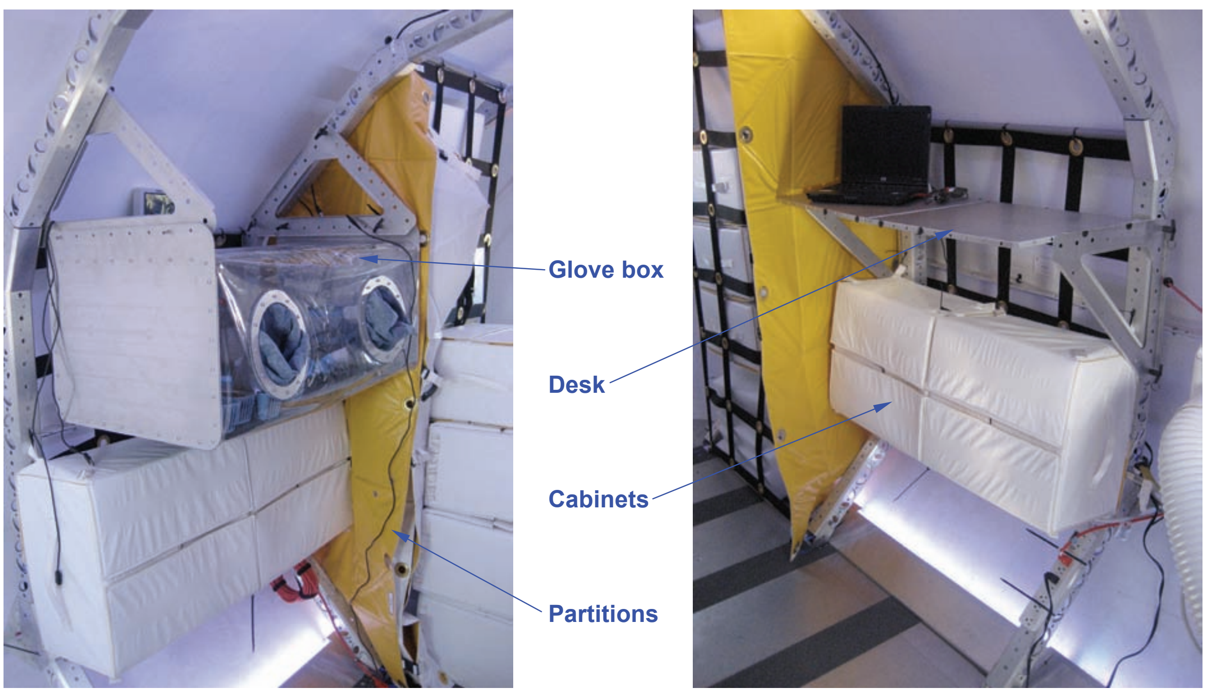

Figure 20: geo-science workstation created from logistics packaging -- operational glove box (left), cabinets and counter top (right)

In addition to the right and left halves of the geo-science workstation, partitions and doors were installed using unfolded L2L2009 CTBs, creating a small compartment that could be sealed off from the rest of the Microhab.

C. Logistics-2-Living on the Moon

In parallel to the Logistics-2-Living design studies, the NASA Lunar Surface Systems (LSSP) team undertook several architecture studies for a lunar outpost (Toups, Kennedy 2009). The studies mainly centered around a horizontal cylindrical habitat module design (Kennedy, Toups, Rudisill 2010) and a vertical cylinder pressure vessel module (Howe, Spexarth, Toups, Howard, Rudisill, Dorsey 2010). These on-going studies assume a multi-mission outpost build-up, where hardware and supplies are delivered in twenty plus missions to the lunar surface. The studies have ranged from about 900 to 1442 surface days, which estimated results in between 1300-1700 CTB units delivered to the surface.

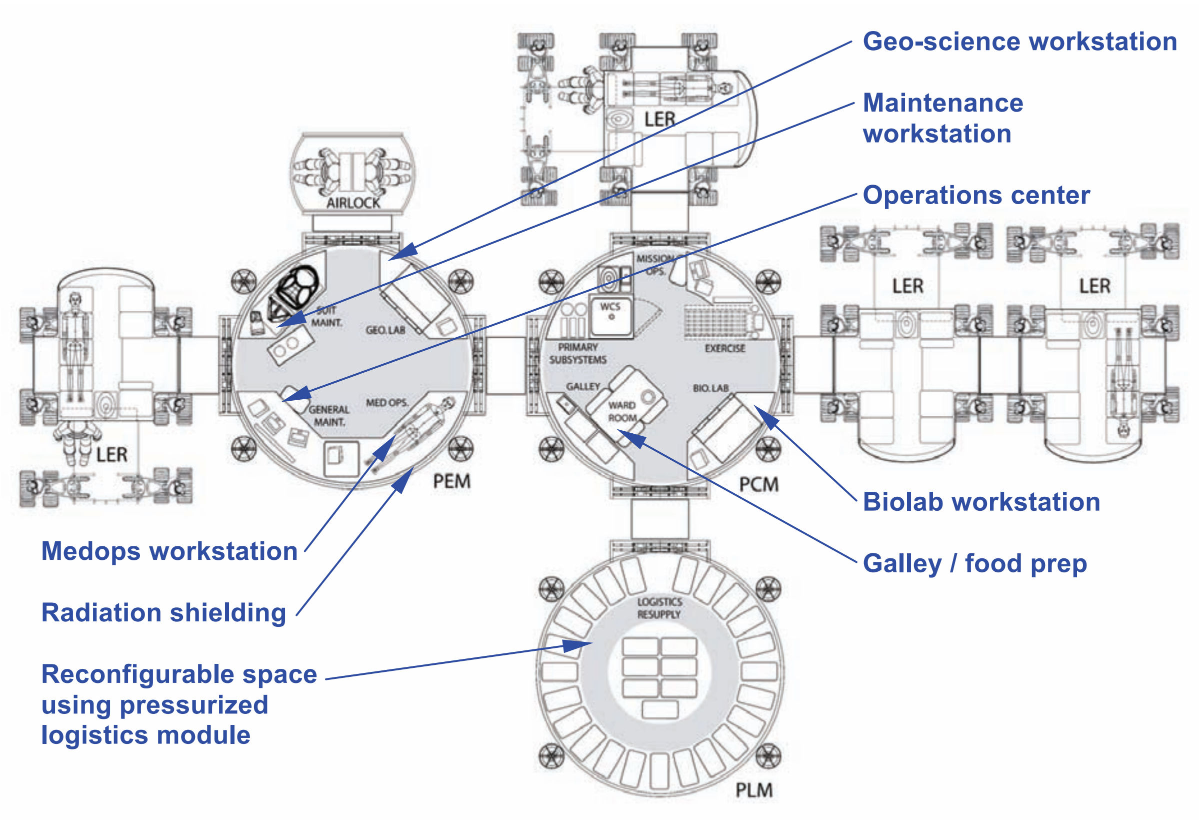

Figure 21: LSSP 'Scenario 12.1' Lunar outpost layout, and potential applications for L2L concepts

The Microhab exercise was configured to resemble the horizontal cylinder, but is was assumed that L2L systems could be applicable to any number of habitat module geometries, both on planetary surfaces (moon, Mars, etc) or in deep space. Figure 21 shows the lunar outpost layout for vertically-oriented pressure modules (Figure 23), listing the various functions that could be affected by dual-use L2L concepts. In addition to interior uses, hydrogen-impregnated CTBs may be used to drape across the outside of habitats for radiation shielding, and photovoltaic surfaced rectangles can be used to supplement power arrays (Figure 22).

Applying the L2L concept to a lunar outpost, estimates for outfitting ranged from 1400-1800kg, depending on functions included in the outpost complete and configurational differences. It was estimated that a major bulk of that mass, 1200-1600kg could be eliminated by applying L2L concepts. The actual mass of the logistics packaging for 1300-1700 CTB units would be 2600-3400kg, meaning that discarded packaging may go down to about 400-1800kg. If additional uses, such as shielding, waterwalls, and exterior in-situ walls and berms are able to make use of the discarded packaging, unused material may eventually go down to zero.

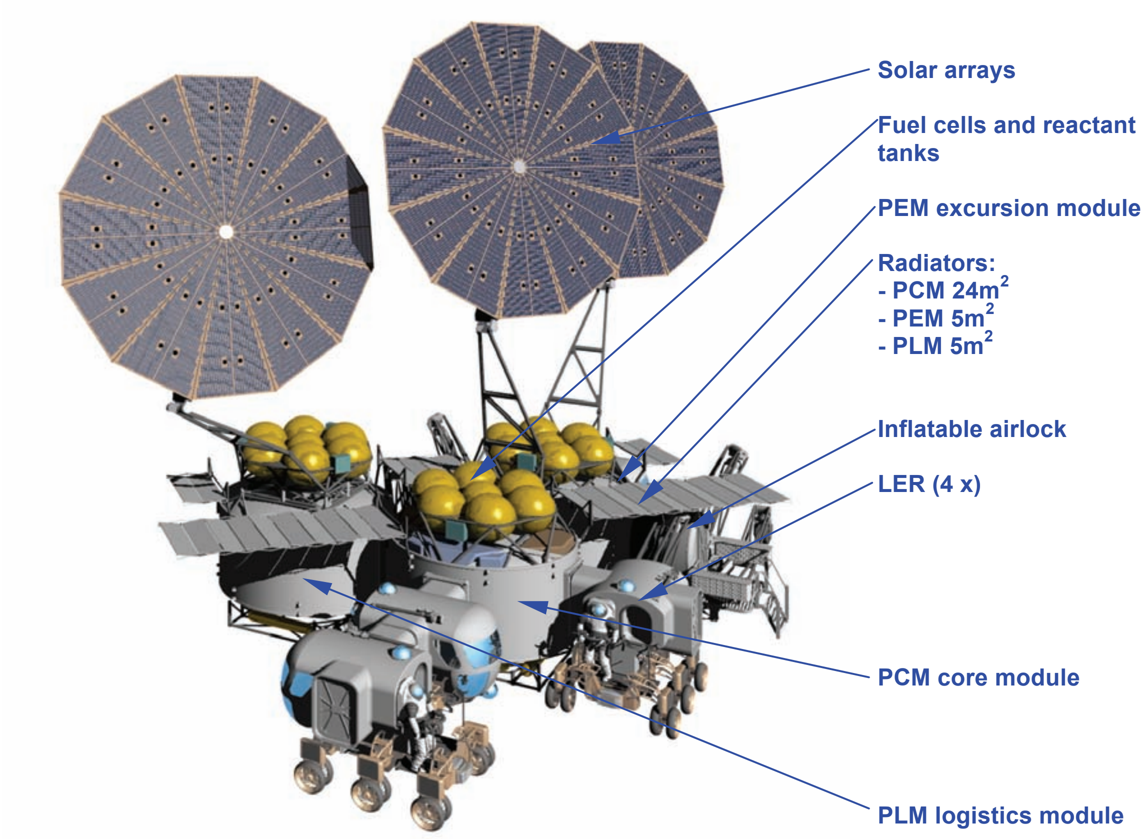

Figure 22: LSSP 'Scenario 12.1' Lunar outpost, showing large power arrays required for operation

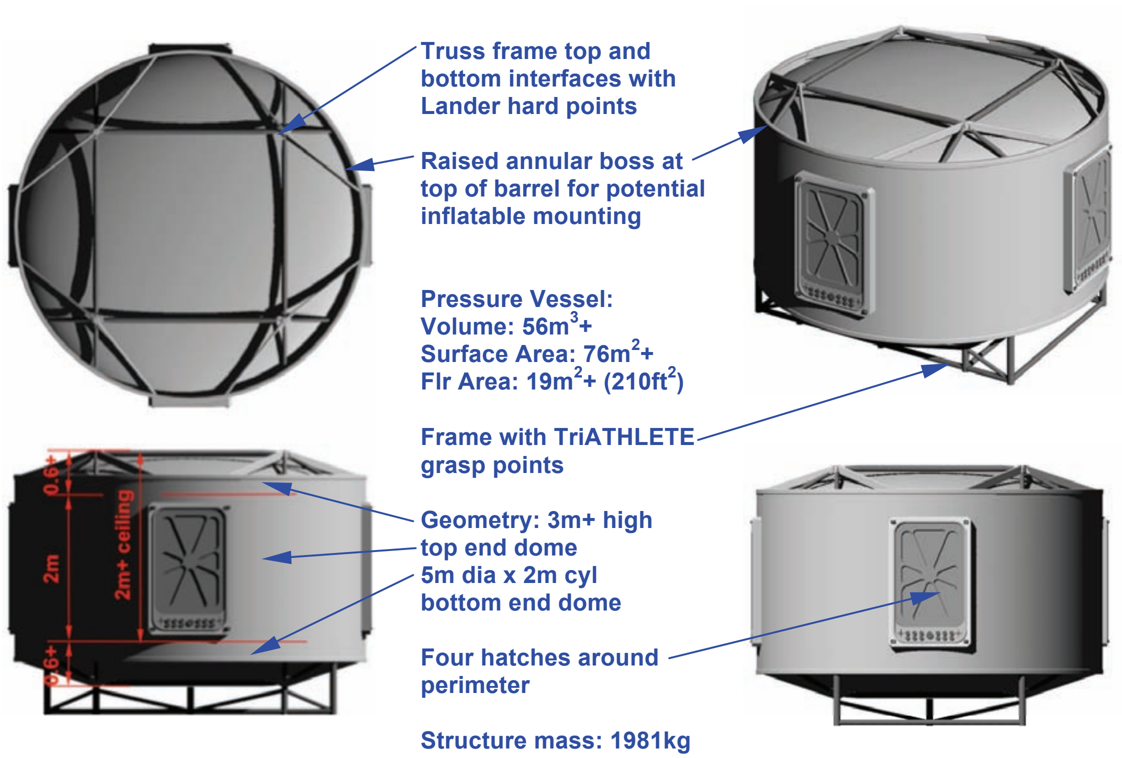

Figure 23: vertical cylinder habitat

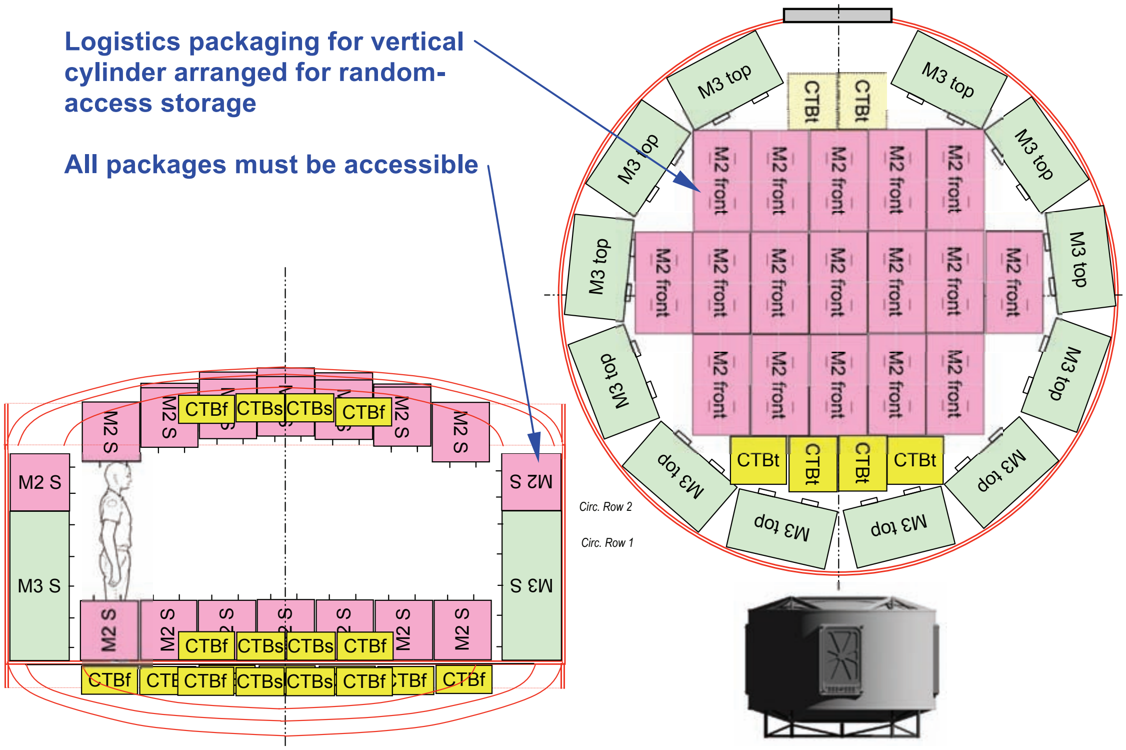

Figure 24: logistics packaging for vertical cylinder logistics module (prepared by NASA LSSP logistics team)

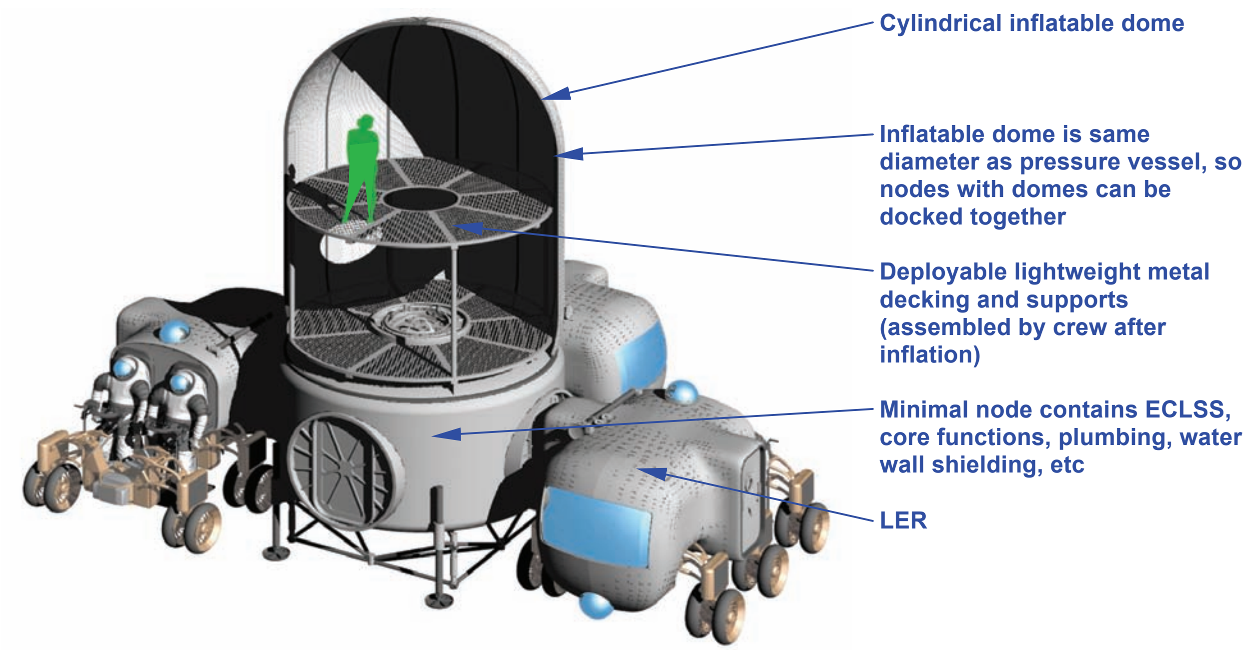

Figure 25: vertical habitat expansion concepts, including inflatable attic space -- can Logistics-2-Living concepts be applied to other aspects of remote human habitats?

D. Future Field Tests: The Habitat Demonstration Unit (HDU)

The Microhab test module functioned as a pre-cursor to a higher fidelity habitat test article for follow-up research. The NASA Architecture Lunar Surface Systems Project (LSSP) Habitation team has spawned a habitat demonstration project that will debut at the D-RATS field test in 2010 (Kennedy, Tri, Gill, Howe 2010). The project is called the Habitat Demonstration Unit (HDU), as a logical next-generation analogue for testing various habitation-related systems. The HDU will be based on the LSSP 'Scenario 12.1' vertical-oriented cylinder habitat pressure vessel design (Figure 23). The HDU will be an integrated element in D-RATS field test that can be docked with other LSSP elements like the Lunar Electric pressurized Rover (LER) and other pressurized extensions.

For D-RATS 2010 the L2L exercise will concentrate on efficient packaging inside the module (Figure 24), and further study on internal outfitting. As part of the lunar outpost design studies, inflatable pressure vessel concepts (full and partial) have been explored. Inflatable structures often create volume when inflated that is devoid of any outfitting. Figure 25 shows an inflatable attic space that may use L2L concepts as a means to produce internal scaffolding and other outfitting.

The HDU and LSSP Habitation Team have also been actively working with universities to get students involved in the design work. Students from several universities have participated in brainstorming sessions for L2L concepts (Duerk 2009).

IV. Conclusion

This investigation shows that Logistics-2-Living concepts combine functions of supply packaging, outfitting, and other hardware and have the potential to reduce mass required to be lifted out of earth's gravity well. Since mass reduction translates into cost savings, design studies that combine multiple uses for various hardware can help reduce mission costs. It is clear that further studies are necessary to compare higher fidelity L2L designs with current logistics systems.

Acknowledgments

Many thanks for the assistance and inspiration of David Nixon, and university students of Donna Duerk (Cal Poly San Luis Obispo) and Michael Fox (Cal Poly Pomona), in addition to the efforts of Hab Team members. The research described in this paper was carried out at the National Aeronautics and Space Administration (NASA), and the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

References

D Duerk (2009). Architecture Student Designs to Support Micro-Hab Sortie Mission, AIAA-2009-6421. *AIAA Space 2009 Conference and Exposition*, Pasadena, California, 14-17 Sep 2009. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

AS Howe; B Sherwood (eds) (2009). AIAA History of Spaceflight series, *Out of This World: The New Field of Space Architecture*, ISBN 978-1-56347-982-3. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

AS Howe; G Spexarth; L Toups; R Howard; M Rudisill; J Dorsey (2010). Constellation Architecture Team: Lunar Outpost 'Scenario 12.1' Habitation Concept. Proceedings of the *Twelfth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments* (Earth & Space 2010); Honolulu, Hawaii, 14-17 March 2010. Reston, Virginia, USA: American Society of Civil Engineers.

KJ Kennedy (2009). Chapter 2: The Vernacular of Space Architecture, pp7-21. In AS Howe & B Sherwood (2009).

KJ Kennedy; TO Tri; TR Gill; AS Howe (2010). The Habitat Demonstration Unit Project Overview. Proceedings of the *Twelfth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments* (Earth & Space 2010); Honolulu, Hawaii, 14-17 March 2010. Reston, Virginia, USA: American Society of Civil Engineers.

KJ Kennedy; LD Toups; M Rudisill (2010). Constellation Architecture Team: Lunar Scenario 12.0 Habitation Overview. Proceedings of the *Twelfth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments* (Earth & Space 2010); Honolulu, Hawaii, 14-17 March 2010. Reston, Virginia, USA: American Society of Civil Engineers.

L Toups; KJ Kennedy (2009). Chapter 16: Lunar Habitat Concepts, pp205-227. In AS Howe & B Sherwood (2009).