Logistics Reduction Technologies for Exploration Missions

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Human exploration missions under study are limited by the launch mass capacity of existing and planned launch vehicles. The logistical mass of crew items is typically considered separate from the vehicle structure, habitat outfitting, and life support systems. Although mass is typically the focus of exploration missions, due to its strong impact on launch vehicle and habitable volume for the crew, logistics volume also needs to be considered. NASA's Advanced Exploration Systems (AES) Logistics Reduction and Repurposing (LRR) Project is developing six logistics technologies guided by a systems engineering cradle-to-grave approach to enable after-use crew items to augment vehicle systems. Specifically, AES LRR is investigating the direct reduction of clothing mass, the repurposing of logistical packaging, the use of autonomous logistics management technologies, the processing of spent crew items to benefit radiation shielding and water recovery, and the conversion of trash to propulsion gases. Reduction of mass has a corresponding and significant impact to logistical volume. The reduction of logistical volume can reduce the overall pressurized vehicle mass directly, or indirectly benefit the mission by allowing for an increase in habitable volume during the mission. The systematic implementation of these types of technologies will increase launch mass efficiency by enabling items to be used for secondary purposes and improve the habitability of the vehicle as mission durations increase. Early studies have shown that the use of advanced logistics technologies can save approximately 20 m^3 of volume during transit alone for a six-person Mars conjunction class mission.

Nomenclature

ACS	=	Advanced Clothing Systems
AES	=	Advanced Exploration Systems
CEP	=	complex event processing
CTB	=	cargo transfer bag
DRA5	=	Design Reference Architecture 5.0
ECLSS	=	Environmental Control and Life Support System
ESM	=	equivalent system mass
EVA	=	extravehicular activity
EXPRESS	=	EXpedite the Processing of Experiments to Space Station
HMC	=	Heat Melt Compactor
ISS	=	International Space Station
kg	=	kilogram
LRR	=	Logistics Reduction and Repurposing
MCTB	=	multi-purpose cargo transfer bag
m^3	=	cubic meter
mL	=	*milliliter*
NASA	=	National Aeronautics and Space Administration

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NHV	=	net habitable volume
REALM	=	Radio Frequency Identification-Enabled Autonomous Logistics Management
RFID	=	Radio Frequency Identification
SBIR	=	Small Business Innovation Research
3D	=	three-dimensional
TtG	=	trash-to-gas
UWMS	=	Universal Waste Management System

I. Introduction

NASA's recent Pioneering Space memo describes the long-term sustainable deep space exploration architecture termed the "Evolvable Mars Campaign."[1] The Evolvable Mars Campaign clearly indicates that increases in reuse, sustainability, and in-situ resource utilization are required to achieve Earth-independent-type missions. It recognizes that International Space Station (ISS) and shorter cis-lunar missions are required to prove out technologies that will be used for Earth-Mars conjunction opportunity missions. In addition to the possible reuse of vehicle modules in the evolvable campaign, it is possible to reuse the logistics from both shorter and longer missions to build capability and resources over time. The Advanced Exploration Systems (AES) Logistics Reduction and Repurposing (LRR) project is developing a set of technologies to reduce crew consumables and provide methods for both stabilizing waste and repurposing waste as a resource. This paper provides a description and the challenges of the six LRR technologies under development and how they will be demonstrated on the ISS to address habitability, logistics, and life support performance needs for exploration. The six LRR technologies each address a different logistics reduction goal.

- The Advanced Clothing Systems (ACS) uses advanced commercial off-the-shelf fibers and antimicrobial treatments with *the goal of directly reducing the mass and volume of a logistics item*.
- The Radio Frequency Identification (RFID)-Enabled Autonomous Logistics Management (REALM) uses RFID technologies for three-dimensional (3D) localization of crew and logistics items. *The goal is that RFID will save crew time and allow logistics packaging to be driven by volumetric efficiency rather than crew time.*
- Multi-purpose cargo transfer bags (MCTBs) can be unfolded after launch and used for crew outfitting. *The goal is that repurposing logistical items avoids flying separate items to meet the cargo function and the outfitting function.*
- The Heat Melt Compactor (HMC) mechanically compacts trash while heating to produce stable tiles that can be used for radiation shielding. The waste volume is significantly reduced and water is recovered for life support. *The goal is to process spent logistical items to provide a secondary function, increase habitable volume, and help close the life support water loop.*
- The trash-to-gas (TtG) technology uses thermo-chemical processes to deconstruct trash into its hydrocarbon constituents and recombine it to form useful gases for propellant or life support. *The goal is to deconstruct spent logistical materials and reconstruct them to primary gases or as a means of reducing waste volume.*
- The Universal Waste Management System (UWMS) is a compact metabolic waste collection system (i.e., toilet). The UWMS will incorporate a high degree of component integration to minimize the installed mass and volume as well as minimize the component and consumable replacement. *The goal is to improve a critical life support system to reduce its logistical burden.*

In addition to the technologies themselves, the AES LRR project has developed logistics and waste models to determine the mass and volume benefits of the LRR technologies. The basic model was described previously and primarily focused on the mass and major chemical makeup of each item.[2] Previously presented results from the LRR model have been for a 1-year, four-crewmember microgravity mission beyond low Earth orbit. In this paper, we apply the model to a six-crewmember Mars transit mission. The LRR model only includes crew-related logistics (clothing, hygiene items, food, extravehicular activity (EVA) and medical supplies, other crew supplies, and life support system consumables) and is based on ISS data. Figure 1 shows that the LRR model predicts a total of 8,055 kg and 28.7 m^3 of crew-related logistics are required for a crew of six during a yearlong transit to and from Mars. Use of the logistics results in trash and human wastes (clothing, food packaging, used crew items, feces, urine brines, other) adding up to 3840 kg. This waste stream represents both an area for reduction and a potential resource.

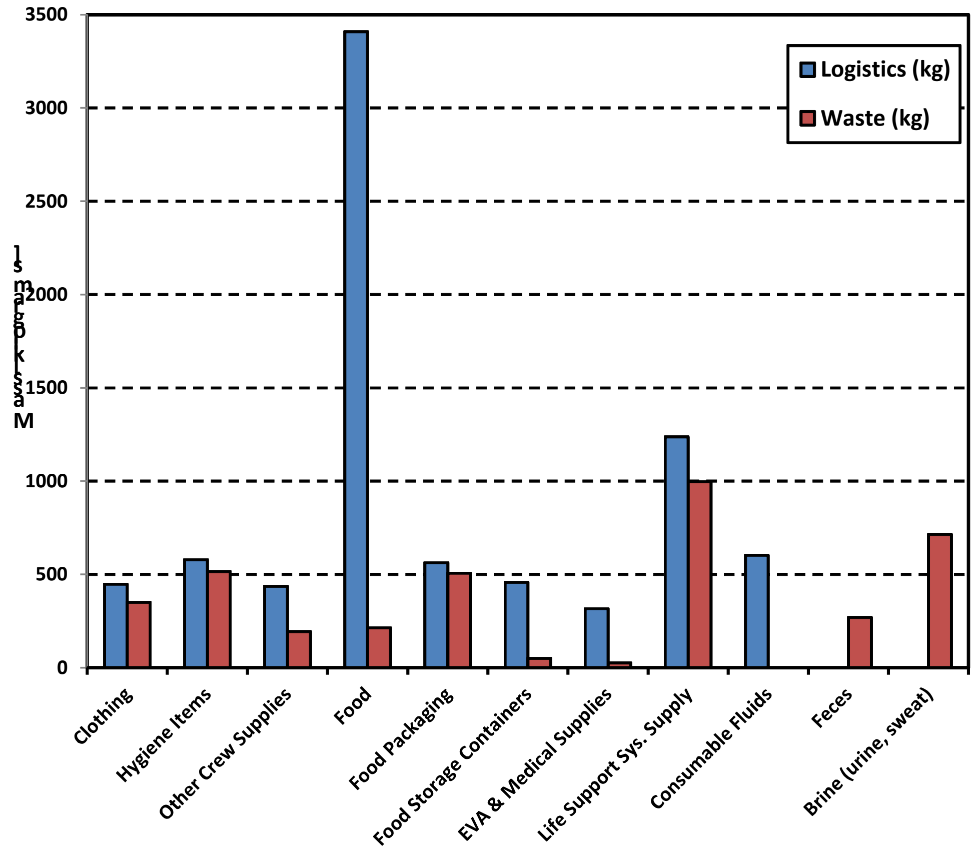


Figure 1. LRR crew-related consumables and waste mass for a six-person crew on a 1-year Mars transit mission.

II. Logistics Reduction Technology Descriptions

For each technology, a general description, how they benefit exploration, and references to more detailed descriptions will be provided. The combined benefit to exploration missions are estimated for an Earth-Mars conjunction class mission with a focus on describing the volume benefits during transit.

A. Advanced Clothing Systems Technology Description

The current clothing state-of-the-art on the ISS is disposable clothing with no laundry provisions. Most ISS clothing articles are cotton-based fibers for crew comfort, and the fibers char in response to high heat. Hence, clothing mass is essentially proportional to number of crew and duration of mission at approximately 0.2 kg/crew-day,[2] Each article of clothing has a different use period, but all become trash after use. The LRR ACS has been investigating advanced commercial off-the-shelf fibers and antimicrobial coatings for exercise and some routine-wear clothing items. If clothing can be worn longer, it directly reduces the logistical mass and volume. This longer wear period from ACS will delay the need for laundry system development. A trade study that compares the equivalent system mass of laundry with and without ACS is under way and will be published next year, but the preliminary breakeven point is approximately ½ to 1½ years, depending on the mission and type of laundry system. If laundry can be deferred until planetary surface missions, the complex challenges of solid, liquid, gas separation in microgravity can be avoided.

Last year, ACS conducted ground tests of exercise clothing with approximately 100 participants. The ground test evaluated fabrics (cotton, polyester, polyester/cocona blend, modacrylic, and wool), different weaves, and either treated with a silane quaternary ammonium salt antimicrobial agent or untreated.[3] Antimicrobial agents were investigated because odor from microbial breakdown of sweat compounds is one the parameters that limit the duration of clothing life. Test participants performed cardiovascular exercise in a controlled environment for 1 hour a day for a minimum of 5 days a week to emulate ISS exercise. The crew wore the garments until they were unacceptable for additional use. Summarizing the results of the ground study, the antimicrobial agent did not significantly improve performance of polyester, polyester/cocona, or wool. The antimicrobial agent did increase use time for cotton fabrics, but untreated wool actually had longer use time than the antimicrobial-treated cotton. Compared to the untreated cotton baseline, untreated wool could be worn about 80% longer in the ground study.[3]

The ground test data were used to determine the final selection of clothing for an ISS technology demonstration for Increments 39/40 (July-September 2014). Two types of exercise shirts, one type of exercise shorts, and two types of routine-wear shirts representing a range of fabric types (e.g., wool, polyester, and modacrylic) and weaves were selected. Approximately 80 clothing articles are scheduled for launch on Orbital flight 2 and Automated Transfer Vehicle flight 5 in July 2014 (Fig. 2). Prelaunch crew evaluations are being performed for each of the US and Russian crewmembers to establish a terrestrial baseline for comparison. On orbit, the crew will complete periodic evaluations, and crew debriefs will be conducted in 2015 after the crew returns from orbit.[4] Results from the ground and on-orbit tests will be published in the summer of 2015.

If the ground test data are validated by the on-orbit experiment, the longer wear time combined with the lighter weight fabrics will reduce mass and volume for exploration. The same types of fabrics can then be applied to a wider range of garments for a greater mass and volume benefit to exploration missions.

Figure 2. Portion of ACS clothing delivery for ISS Technology Demonstration.

B. Multi-purpose Cargo Transfer Bag Technology Description

The MCTB concept will repurpose items originally used for interior cargo packaging into useful crew outfitting hardware. Cargo items include cargo transfer bags, foam packaging, and stowage racks. Cargo transfer bags (CTBs) have represented a common stowage unit for the Space Shuttle and ISS. The CTBs have a volume of 0.053 m^3. The CTBs are suitcase shaped and more than 260 CTBs would be required for a 1-year six crew mission if used exclusively for packing crew consumables. LRR has developed MCTBs that provide the required shape and restraint for launch but can be unfolded for secondary crew outfitting functions. The MCTB is held in the suitcase shape with several snaps and zippers (Fig. 3). Previous concepts have included lightweight crew quarters, solar radiation storm shelters,[3,5] partitions, acoustic absorption, and water processing.[6] The secondary use of the MCTB must be known so that small specific features in materials of construction, attachments, and keep-out zones can be incorporated into the original design. It is envisioned that a mission would have several types of MCTBs for specific purposes packed with logistical items that are used in the early phase of the mission.

LRR is pursuing the application of the MCTB to address excessive noise from the ISS treadmill as a potential flight demonstration in 2015. The ISS treadmill generates sound levels of 85 dBA at high speeds. The sound is reflected off surrounding hard surfaces back to the crewmember. Dedicated acoustic blankets could be flow and applied to three surrounding surfaces. Modeling indicates that acoustic treatments can provide a 3-decibel reduction, which represents a 50% reduction in sound power level (on a log scale). This would require approximately three

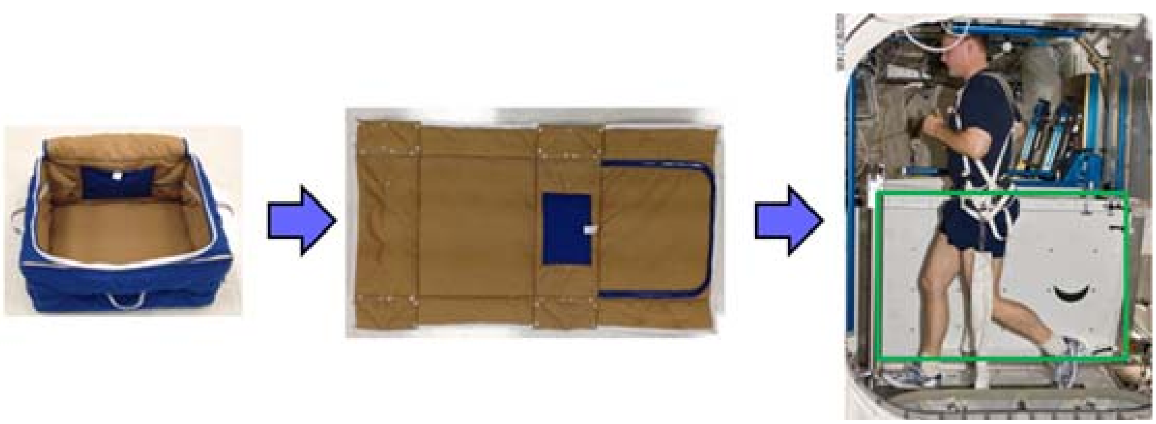


Figure 3. Repurposing of MCTB for mounting on ISS Waste and Hygiene Compartment wall to mitigate treadmill acoustic noise.

CTBs to contain the blankets. The CTBs used for launch would then become trash. LRR has worked with the Johnson Space Center Acoustics Office to perform acoustic transmission coupons of fabric layups and model overall acoustic damping. LRR has fabricated a MCTB with the acoustic layup to demonstrate it can still be folded into the CTB shape for launch. Two rack surfaces have relatively large keep-out zones that do not lend themselves well to the launch configuration of the MCTBs. The third surface is the ISS waste and hygiene compartment wall with no keep-out zones, so it is a good application of the MCTB approach using two MCTBs (Fig. 3). Using this approach, two acoustics MCTBs can hold the remaining acoustic blankets. This results in a 30% reduction in launch volume (two MCTBs rather than three CTBs) and no residual waste (because the MCTBs are used). LRR has estimated that approximately 50% of the CTBs required for an exploration mission could be repurposed for vehicle outfitting,[2] which would save significant mass and volume.

C. Radio Frequency Identification-Enabled Autonomous Logistics Management Technology Description

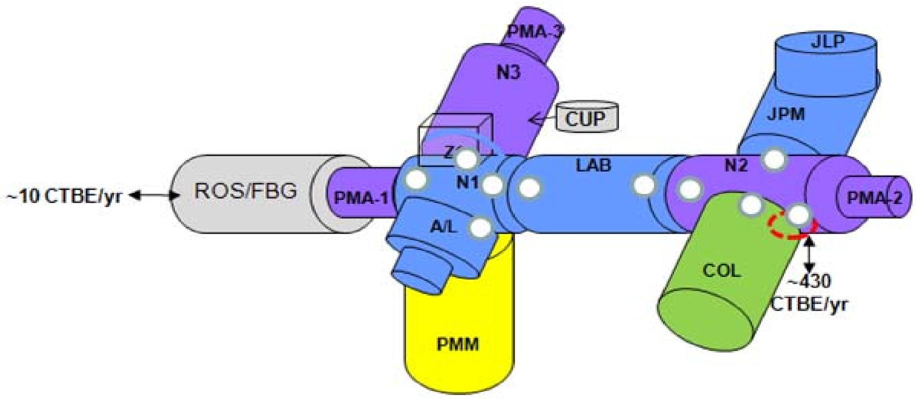
REALM is a broad area, but LRR will focus on RFID technologies, 3D localization strategies, and complex event processing (CEP) to enable automatic inventory tracking as resources move around a vehicle. These functions have the potential to dramatically reduce on-orbit crew time required to perform general inventory management and searching for misplaced or lost items. Returning ISS crews indicate that a substantial amount of time is spent on looking for items to perform a task. Additionally, some items become “lost,” including relatively large items such as CTBs and contingency water containers. It is difficult to quantify the amount of lost crew time, but cost estimates based on crew time start at more than $1M per year based on previous studies[7] and the current estimated rate for crew time.

On-orbit crew time is a very limited resource. Consequently, cargo packing configurations for ISS are currently driven by crew-time considerations. Like items are packaged together so their location is known. This often results in less-than-ideal volumetric packing efficiency because unlike items are not used to fill the “voids.” The voids are typically filled with foam to maintain the CTB or cargo carrier shape to control the position of restraint straps. Four post Space Shuttle resupply flights were analyzed, and approximately 37% of the cargo volume was occupied by foam.[3,8] Some foam is required to protect sensitive hardware areas (e.g., connectors, displays, fluid lines, etc.), but approximately 50% of the foam was volumetric filler to maintain bag shapes. If REALM is implemented, LRR estimates foam can be reduced by 50%, which will directly reduce the launch volume, the number of CTBs, and waste volume.

REALM investigated three areas over the past year: dense zone readers, sparse zone readers, and a CEP. Dense zones are physical volumes with conductive boundaries that contain the RFID energy and are able to accurately read large numbers of internal RFID tags. Sparse zones are areas exclusive of the dense zone. All RFID items could be read nearly 100% of the time with a sufficient number of dense and sparse readers. However, due to the limited mass, volume, and available power of exploration vehicles, the number of dense and sparse zone readers will be limited. Although RFID technology is capable of accuracies comparable to barcode readers when human feedback is employed, that level of accuracy is typically sacrificed in autonomous operations, even in benign scattering environments. In the complex scattering environments presented by space vehicles and the presence of metallic and liquid items, 100% direct read accuracy is not obtainable. In the sparse zones, a study of the read accuracy from fixed portal readers indicated an accuracy of about 75% of tagged items within a CTB, with content including a mixture of nonconductive, conductive, and liquid items.[9] Current studies will evaluate the ability of CEP to infer the location of items based on historical data derived from dense and sparse zone readers, and hence improve the accuracy of the inventory database.

Over the past year, an RFID-enabled MCTB was built as a dense zone reader utilizing a conductive fabric layer sewn into the MCTB walls. The conductive wall, in addition to improving the read accuracy for internal items, prevents reading tags external to the MCTB to ensure responding tags are unambiguously localized to the interior. Reading efficiency is similar to previous RFID containers.[7] However, the MCTB soft-sided container is lower mass, utilizes an e-textile antenna feed, and could be later used for vehicle outfitting. LRR has had initial discussions with ISS crewmembers and ISS cargo managers to define several concepts of operation for RFID MCTB type bags.

REALM is planning on establishing hatch reader infrastructure in ISS Node 1, Node 2, and US Laboratory as a flight experiment in 2015, with notional reader antenna locations as depicted in Fig. 4. The readers for this experiment are based on a design for the ISS Human Research Facility medical drawer that will be activated on the ISS later this year. The sparse zone hatch readers will provide a long-term, real-world, rich-data stream for developing the CEP algorithms for NASA’s exploration logistics management and automation. The initial CEP development will occur on the ground and allow comparison to the existing ISS inventory management system database. The initial CEP spatial resolution, derived from the tag signals received by the readers, is expected to be about one half of an ISS element module.



PMA-2	COL	N2	JPM	JLP	PMP	Lab	Quest	PMA3	N3	N1	PMA1
2%	12%	4%	9%	9%	36%	8%	7%	2%	2%	8%	2%

Figure 4. Distribution of ISS stowage and notional location of RFID hatch reader antennas (white circles) for ISS technology demonstration experiment.

The hatch readers, communication network, and CEP will provide the initial foundation and infrastructure for future RFID experiments involving the RFID MCTB and autonomous robotic free-flyers equipped with RFID readers. Collectively, these extensions will provide additional CEP context, thus enabling finer location resolution and accuracy. REALM will reduce crew time in locating stored items and enable more accurate inventories. Additionally, the accurate 3D localization will enable future automation and wireless sensor capabilities. AES LRR is discussing possible collaboration with the AES Autonomous Missions Operations project on enhancing automatic crew procedure generation and augmented reality technology demonstrations utilizing REALM data.

D. Heat Melt Compactor Technology Description

The HMC provides several benefits from trash processing. Trash from space missions has been analyzed and typically contains greater than 20% plastic and 25% water.[10] The water is predominantly from food and drink residual as well as wipes, and can be recovered for reuse by the HMC. The HMC is a technology for providing a 7:1 reduction in trash volume via compression and application of heat to produce a dry, microbially stable trash tile (Fig. 5). Plastic softens during heating and cools in the compressed state to maintain a dimensionally stable tile. The compaction ratio has the capability to increase habitable volume over the course of a mission. The HMC tiles can serve as the final disposal form or an interim waste storage form until more fully processed by technologies such as TtG. Additional benefits of the HMC tile are that it is relatively high in hydrocarbons (plastics and food residuals) and is useful for solar event radiation shielding. The HMC can reduce the dedicated radiation shielding and water storage masses for exploration.

Figure 5. Example of uncompacted trash and HMC compacted trash.

LRR has designed a high-fidelity flight-like HMC second-generation unit (generation 2) and is completing assembly in 2014, Fig. 6. The unit is being designed for EXpedite the Processing of Experiments to Space Station (EXPRESS) rack interface to enable design transition to an eventual ISS technology demonstration. The HMC will be able to process approximately 1 kg of mixed trash and recover approximately 200 mL of water per batch. The major design challenges of the HMC technology are designing the compaction chamber and its steam vents and seals to be tolerant of the softened plastic and caramelization of food residuals.[10] The major process design challenges including ensuring adequate heating of the low conductivity trash to inactivate microorganisms and sufficiently dry the trash. A proof-of-concept HMC (Gen 1) has been used to study the effects of chamber temperature and internal pressure on tile composition, removed water contaminants, and off-gassing. In general, lower temperatures produce fewer off-gassing compounds but may reduce microbial deactivation effectiveness. More than 80 compounds have been identified in the evolved gases during heating.[11] A large number of these are from food residue. Source contamination control of these compounds is an area of active development and collaboration with the AES Atmosphere Resource Recovery and Environmental Monitoring project. The gas contaminants are planned to be removed by a carbon adsorption bed and downstream thermo catalytic reactor from a Phase III Small Business Innovation Research (SBIR) contract.

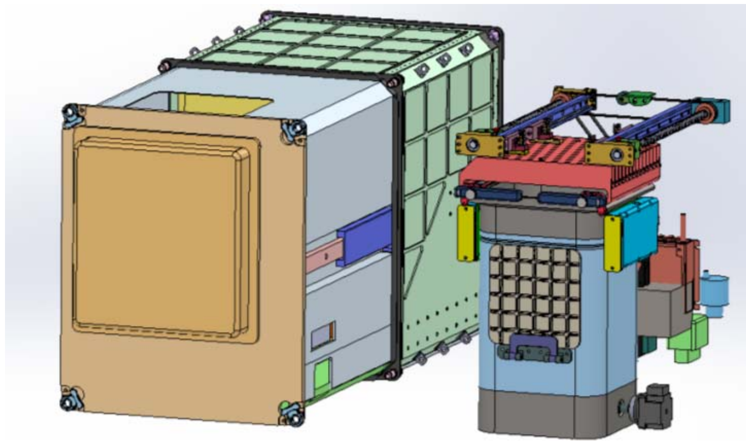


Figure 6. Second generation HMC design.

In addition to regular mixed trash, a limited number of tests have been conducted with only ISS packaging foams to identify the types of gas effluents and determine compaction efficiency. Testing to date indicates HMC can achieve greater than 80% compaction efficiency, which will help reduce the trash volume of foam used to protect hardware during launch.[8]

The compacted foam tiles and mixed trash tiles contain mostly hydrocarbons with an average of 7% hydrogen by mass. This is a less than water and polyethylene at approximately 11% and 14 %, respectively, but is already on orbit and does not require additional launch mass. HMC is working with the AES Radiation project to use HMC tiles as part of their solar radiation storm shelter concepts. HMC has changed the shape of the tiles from the round tiles of the generation 1 HMC to a square with rounded corners for the generation 2 HMC, Fig. 7. This shape adds complexity to the HMC compaction chamber but will provide more uniform radiation shielding. The size of the tile was also selected to allow efficient volumetric storage in CTBs when not being used in a storm shelter.

Figure 7. Example of HMC generation 1 tile (left) and planned generation 2 tile shape to improve storage and use for radiation shielding.

E. Trash-to-Gas Technology Description

The TtG capabilities include processing a wide range of waste materials into gases that can be converted into high-value products or vented as a "jettison function" without an airlock. TtG can produce propellants, and oxygen and water for life support.[12] LRR waste modeling has estimated the elemental composition of crew consumables waste, and there are significant quantities of oxygen and hydrogen (Fig. 8). In addition to the production of gases, TtG also provides greater than 90% volume reduction with only an ash or a tar residual remaining. All microbial activity is destroyed, which may be beneficial to Mars surface planetary protection goals.

TtG has investigated the use of terrestrial thermo-chemical processes and tested six technologies with an LRR waste simulant in 2012 and 2013. The six technologies included pyrolysis, gasification, incineration, catalytic reduction, steam reforming, and ozone oxidation. A combination of experimental data and system modeling was used to down select to the most promising technology. Steam reforming technology performed the best for both the production of methane and the resistojet gas propulsion scenarios.[13] Funding has been limited, but steam reforming technology development is continuing with work being performed at Kennedy Space Center to improve understanding of the effects of process conditions on conversion kinetics and with a Phase II SBIR steam reformer from Pioneer Inc. that was delivered to the Glenn Research Center.

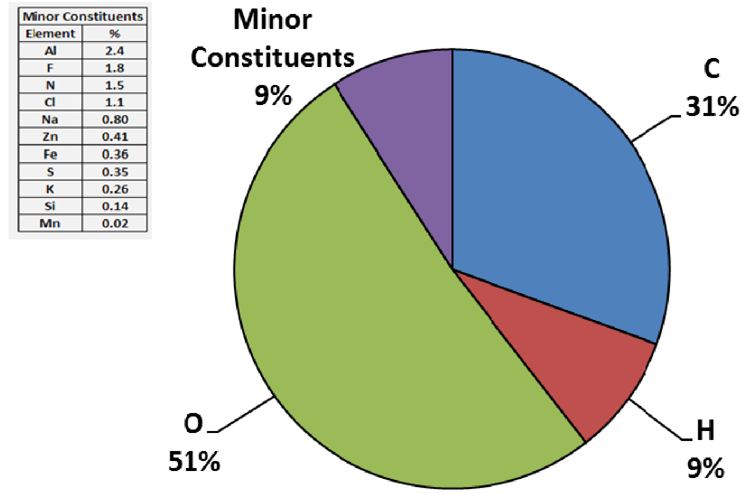


Figure 8. LRR Elemental composition of crew consumables waste stream.

LRR has been performing systems analyses. These analyses have shown that waste processing with steam reforming can be integrated with life support processes such as Sabatier carbon dioxide reduction, and also shares commonality with in-situ resource utilization processes.[14] TtG can accept a wider range of waste than HMC, including life support urine brines, feces, and even the HMC tiles. The ability to process HMC tiles enables the mass of a logistics item to be used three times: once for its original purpose; a second time for radiation shielding during transit; and a third when, at the end of the transit mission, it is converted to propellant. Calculations show that significantly more propellant mass can be generated than the required reactor mass. Sufficient propellant can be produced for refueling small sample return landers from the lunar surface, or can provide station keeping delta velocity in at an Earth-moon Lagrangian point.[15] On a planetary surface, the TtG approach would result in large volume reduction of trash and would potentially be best for planetary missions where planetary protection is important. TtG development is needed to address the safety concerns and equipment mass required to manage the high temperatures and pressures in a space environment. TtG is investigating the possibility of using the ISS combustion facility to obtain improved kinetics and conversion data for future exploration applications.

F. Universal Waste Management System Technology Description

The UWMS is a special case of solid waste collection and has a direct human interface that requires accommodation of a wide range of urine and feces quantities and characteristics.[16] If not adequately captured and contained, metabolic waste can rapidly create an unhygienic condition in the spacecraft due to the biological nature and objectionable odors. As with previous microgravity toilets, the UWMS will use air flow to separately entrain urine and feces. Past and existing microgravity toilets are not completely effective at collecting waste from crewmembers, which results in the escape of material. The escapes result in soiling of the toilet surfaces, the crewmember, and the spacecraft cabin. The United States segment of the ISS uses a Russian toilet to maintain commonality with the Russian system. The Russian toilet requires large installed and consumable masses and volume that would be difficult for exploration missions to accommodate.[17]

Although preliminary component design has started, the UWMS development effort formally begins in late 2014. The UWMS will combine two fans and a rotary air-urine separator to minimize the installed mass and reduce acoustic noise transmission.[18] Urine is pretreated to keep it microbially inactive to protect the rotary separator. The rotary separator either delivers the urine to a storage tank, vents it overboard, or delivers it to the Environmental Control and Life Support System (ECLSS) to recover water via distillation and multifiltration (i.e. ISS or a Mars transit). The UWMS will collect feces events in individual gas-permeable hydrophobic bags to maintain a hygienic collection volume. The bags are currently released into a rigid cylinder and a thin flexible disk is placed above it. The bags are then manually compacted and the flexible disk has a ratchet-like movement with the cylinder walls.

The compaction provides approximately 60% volume reduction and the disk ratcheting prevents spring back of the wipes and hygiene products. After the initial UWMS is developed, the canister will be optimized to allow improved compaction efficiency and allow for processing of the feces and paper products in either the HMC system or the TtG system. Feces contains about 75% water by mass, so it can help to close the ECLSS water balance and reduce waste volume via reuse of disposal canisters. Additionally, a series of crewmember evaluations of seat geometries, air flow, and positioning of the funnel to allow simultaneous urination and defecation are planned to address known deficiencies that lead to urine and feces escape.

The UWMS team is planning to develop a flight test article for testing on the ISS in 2018. The flight test will evaluate several seat improvements, the dual fan separator performance (including operation after a quiescent period), and fecal compaction effectiveness. This test will allow further design refinement for Orion and longer exploration missions.

III. Integrated Logistics Reduction Volume Benefits Analysis

Since the focus of this paper is volume savings, the volume reduction benefit of each technology will be described and quantified below for our reference mission. The selection of a reference mission is important to allow eventual application to larger integrated mission analysis. Logistics mass and volume is strongly dependent on the mission duration and crew size. Short missions may benefit from direct logistics reductions but not from processing wastes. Longer missions are required to have the volume reduction exceed the increase in launch mass and volume of the processing equipment. For HMC, the breakeven point can be as short as 15 days for volume. Missions to a Lagrangian point are viable, and intermediate length missions of 21 to 90 days are on the NASA roadmaps. Planetary surface missions being discussed can be short sortie missions of 10 days or long durations exceeding 500 days. The transit to Mars represents sufficiently long missions where the crew is likely not going to venture outside of the pressurized volume. These mission classes will represent situations where internal volume is particularly important to the crew.

A. Reference Mission Description and Assumptions

For the purposes of calculating mission benefits in this paper, the Mars transit portion of NASA's Mars Design Reference Architecture 5.0 (DRA5) was selected as a long-duration microgravity mission.[19,20,21] The total mass and volume for this class of mission severely challenge our launch capability, therefore any savings in mass and volume will be particularly valuable. A brief overview of the mission used for the LRR analysis follows. The conjunction class long-duration stay at Mars (up to 550 days) was selected for this analysis; however, savings computed below are only for the microgravity transit portion of the mission. Most, if not all, of the technologies can also be incorporated into the Mars surface habitat, resulting in additional benefit. A brief overview of the mission parameters are described here. The Mars DRA5 documents have significant additional details. The conjunction class mission provides an overall lower propulsion energy requirement and relatively short transits to and from Mars. A launch opportunity to Mars occurs every 2 years during planetary conjunction. A longer surface stay is required to allow for Mars and Earth to realign for a low-energy return. Transits each way are different for every launch opportunity due to planetary orbit variations, but transit times can vary from 60 to 200 days depending on planetary alignment particulars and propulsion delta V capability. LRR assumed a more conservative 182.5-day transit each way to capture the majority of launch opportunities. This also results in exactly 1 year of supplies required aboard the transit vehicle. This analysis did not include the contingency food on the transit vehicle that DRA5 included in case a landing was not possible. LRR used the same basic vehicle parameters for the Mars Transit Habitat as the DRA5, which provides habitation and life support functions for a crew of six in a rigid 7.2-m-diameter pressure shell with 85% water closure and a habitable volume of 130 m^3 (addendum 2 aggressive case). The DRA5 presents the vehicle configuration in terms of mass per major system or function, not volume. This analysis used the DRA5 and combined it with the LRR waste and logistics model and data from other sources to calculate the volumes. For the baseline case usage rates, the corresponding trash generation rates for transit were calculated. The LRR technologies were then applied to estimate the volume savings.

Logistics reduction technologies reduce mass and volume in several ways. This analysis does not include the surface portion of the mission to allow analysis of a single vehicle element, only the transit portion to and from Mars. Currently on the ISS, there is little reuse except for logistics CTBs being repacked with trash for disposal or small improvisions by the crew. The vast majority of logistical items become trash (defined here as packaging materials, dirty clothes, spent consumables, etc.) and waste (metabolic waste, ECLSS urine brine, etc.). LRR technologies can significantly reduce launch logistics by directly reducing consumables or by repurposing or processing the trash/waste into a useful product or item. Figure 9 provides a schematic of the major logistics to trash flows without and with LRR technologies. The figure illustrates how much less trash and waste is generated with LRR technologies, thus contributing to improved sustainability of space exploration. Quantification of the savings is provided subsequently.

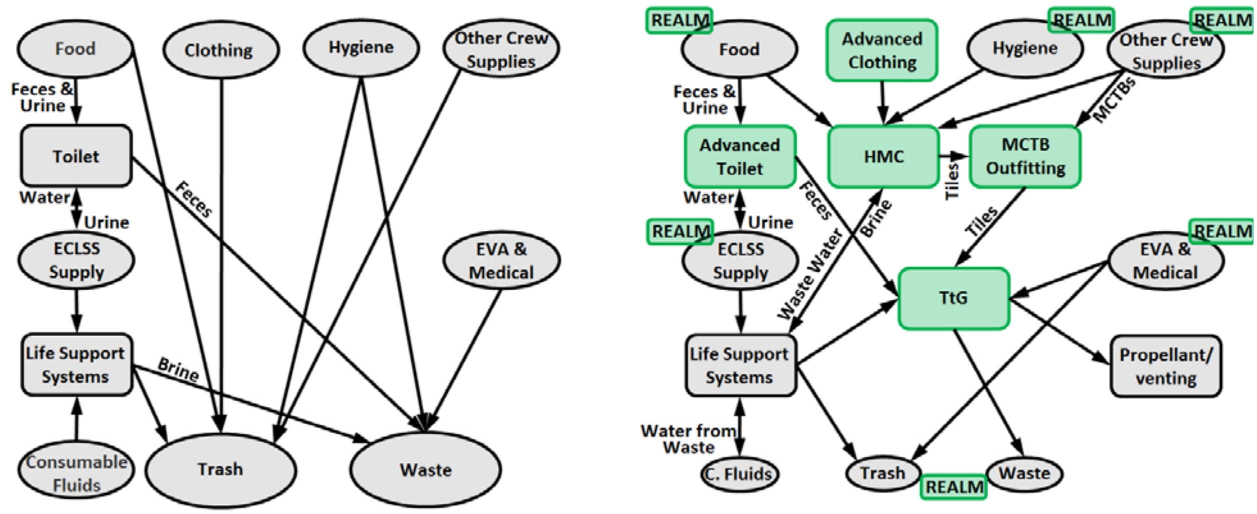


Figure 9. Logistics to trash flow schematic for the ISS (left) and implementing all LRR technologies (right).

B. Volume Benefits of Logistics Reduction and Repurposing Technologies

In this section, we apply all the previously discussed LRR volume savings to the transit portion of a Mars mission to illustrate the synergistic benefits. A summary of each technology's benefit is provided with a very succinct description of the process and analysis. The technology description section above provides reference publications that describe the technologies in detail.

1. *Volume Benefits of Advanced Clothing System*

The lighter-weight and longer-wear materials of the ACS compared to current ISS clothing were substituted for exercise clothing, other T-shirts, underwear, and socks, resulting in a 14% decrease in volume due to the ACS. This benefit is realized from the very beginning of the mission since less clothing must be packed. Round-trip savings for the crew of six are shown in Table 1.

2. *Volume Benefits of Multi-purpose Cargo Transfer Bags*

MCTBs can be used to launch supplies and then reused for various purposes, as discussed above and in Ref. 2. The savings predicted in Ref. 2 are due to extra items that do not have to be launched for crew quarters; partitions and sound absorption were scaled to a crew of six and are shown in Table 1.

3. *Volume Benefits of Radio Frequency Identification-Enabled Autonomous Logistics Management*

As described above, REALM technology can be used to better track and find items when they are needed during the mission and allow launch packing for optimal volumetric efficiency. It is believed that the packing efficiency of MCTBs can be increased from 75% to 95% through elimination of filler foam and less need to group items for crew ease of location. This translates into the volume benefit shown in Table 1 for the transit mission. Of course, the crew will also benefit by spending less time looking for items. This process should also allow for more freedom regarding temporary stowage.

4. *Volume Benefits of Heat Melt Compactor*

The AES LRR model predicts that 2854 kg of trash will be generated on the way to and from Mars. Of this, 1822 kg is suitable for processing in the HMC. Human wastes are not included in this value and are considered under TtG. An updated prediction of 7:1 compression ratio for the HMC was used to calculate that this trash volume could be reduced from approximately 15 m^3 to 2.5 m^3, resulting in the savings shown in Table 1.

Volume reduction of water recovered by HMC: Since the HMC recovers water from trash, it could produce 343 kg of water during the mission, resulting in less water brought from Earth. If equipped with brine processing bags, the HMC could also process urine brine from the wastewater processor, resulting in an additional 540 kg of water saved. Corresponding volume savings are shown in Table 1. If the mission is already "water rich," then both of these may not be required; however, excess water could be used for EVA cooling and/or radiation water walls.

Volume reduction of radiation shielding by HMC: Since the HMC makes tiles from trash that can be used to supplement or replace radiation shielding provided by dedicated materials or logistics such as food, use of these tiles can reduce the volume of dedicated shielding that must be launched. The savings shown in Table 1 come from multiplying the volume of tiles produced from trash by 8/14, the ratio of hydrogen molecules in HMC tiles versus polyethylene shielding, since the tiles will not be quite as effective as a dedicated shield.

5. *Volume Benefits of Trash-to-Gas*

If a TtG reactor is included on the Mars transit vehicle, it can process the feces and toilet paper from the UWMS throughout the mission as well as a few other items that may not be considered appropriate for the HMC, such as medical waste that may be considered a biohazard. Although the urine brine was assumed to be processed in the HMC above, it could also be processed in TtG. Thus, these two disposal technologies can provide some unlike redundancy for each other. Savings due to the processing of feces will allow many fewer waste canisters to be brought on the mission. This will be enabled by future design enhancements of the UWMS, as discussed below.

The TtG reactor can also allow reuse of the same materials three times on the mission. On the return journey, the HMC tiles, which are already reprocessed trash, can be processed again by TtG to create propellant. Savings in Table 1 were calculated based on making methane in a steam reformer. This propellant could be used for final course corrections or to jettison the unneeded stages of the return vehicle. In this case, the volume savings would be for unpressurized space since any methane displaced from the launch manifest would have been stored outside as liquid methane. The volume savings due to TtG, which total 5 m^3, are shown in Table 1. The estimated volume of the TtG reactor (1.2 m^3) has already been subtracted from the volume savings for "all waste processing."

6. *Volume Benefits of Universal Waste Management System*

Careful design of UWMS will allow feces to be transferred to TtG for processing and return of the waste collection canisters to UWMS for reuse. Even though those details have not been worked out yet, the incentive is great due to the savings in number of canisters required for the mission. With a disposable canister, it is estimated that 3.9 m^3 of storage volume is required, before and after use, on the transit habitat. Taking into account that some supplies could be packed into these canisters before use and that 10% are still needed for use and reuse yields the volume savings shown in Table 1.

7. *Integrated Volume Benefits of Logistics Reduction and Repurposing*

Taken all together, the volume benefits described here add up to about 21.7 m^3 by the end of the transit mission. Of this, 19.8 m^3 are savings in pressurized volume, which are more valuable due to the penalty of pressure shell mass.

Table 1. Round-trip Mars Transit Volume Savings of Logistics Reduction Technologies (crew of 6; 365 days round trip).

Total LRR Technology and Benefit	m^3/year
ACS - volume savings	0.31
MCTB - volume savings	0.75
REALM - volume savings	0.40
HMC - volume reduction of trash	12.48
HMC - volume reduction of radiation shielding	1.2
HMC - volume reduction of water recovered	0.9
HMC - volume reduction due to brine processing	0.7
TtG - volume savings for all waste reprocessing	1.9
TtG - volume savings for misc. processing	0.26
UWMS - volume savings for feces & toilet paper processing	2.8
Total volume savings (by end of mission)	21.7

Even though a human Mars mission may be more “mass limited” than “volume limited,” volume inside the crew’s pressurized cabin will always be at a premium. Net habitable volume (NHV) is the functional volume left available to the crew after accounting for the loss of volume due to deployed systems equipment, logistical supplies, trash, and any other structural inefficiencies and gaps that decrease the functional volume. In other words, once the vehicle is loaded up, the space left is NHV. LRR technologies will help make this as large as possible. Table 2 takes a closer look at the volume savings of the LRR approach during the *outbound* journey of the Mars Transit Habitat. Savings are allocated to the category of consumables that they most influence.

Table 2. Detailed example of outbound leg of Mars Transit Habitat Volumes with and without Logistics Reduction Technologies. All values are in m^3 of volume.

Logistics Category	Earth Departure w/o LRR	Mars Arrival w/o LRR	Earth Departure w/ LRR	Mars Arrival w/ LRR	Type of Savings
Clothing	1.4	0.8	1.1	0.6	ACS - reduce
Hygiene Items	2.8	1.6	2.4	1.4	ALM - efficiency
Other Crew Supplies	3.5	2.2	2.8	1.7	MCTB - reuse
Food System	11.2	6.2	11.2	6.2	
EVA & Medical Supplies	0.6	0.5	0.6	0.5	
Life Support Sys. Supply	8.5	8.5	5.0	5.0	HMC & TtG - reduce waste tanks
Consumable Fluids	0.6	0.6	0.2	0.2	HMC - reuse water
Logistics Total	**28.6**	**20.4**	**23.3**	**15.6**	
Trash	0.0	7.6	0.1	0.2	HMC - reduce, recycle
Total Logistics + Trash	**28.6**	**27.9**	**23.4**	**15.8**	
Percent reduction (%)	**0**	**2**	**18**	**45**	

Figure 10 illustrates graphically how logistics consumables, trash volume, and open “habitable” volume would be divided within the transit vehicle on the outbound journey to Mars, with and without application of the LRR technologies. Volumes of the vehicle systems such as power, ECLSS, and communications are not included here since they are expected to remain the same during the entire mission.

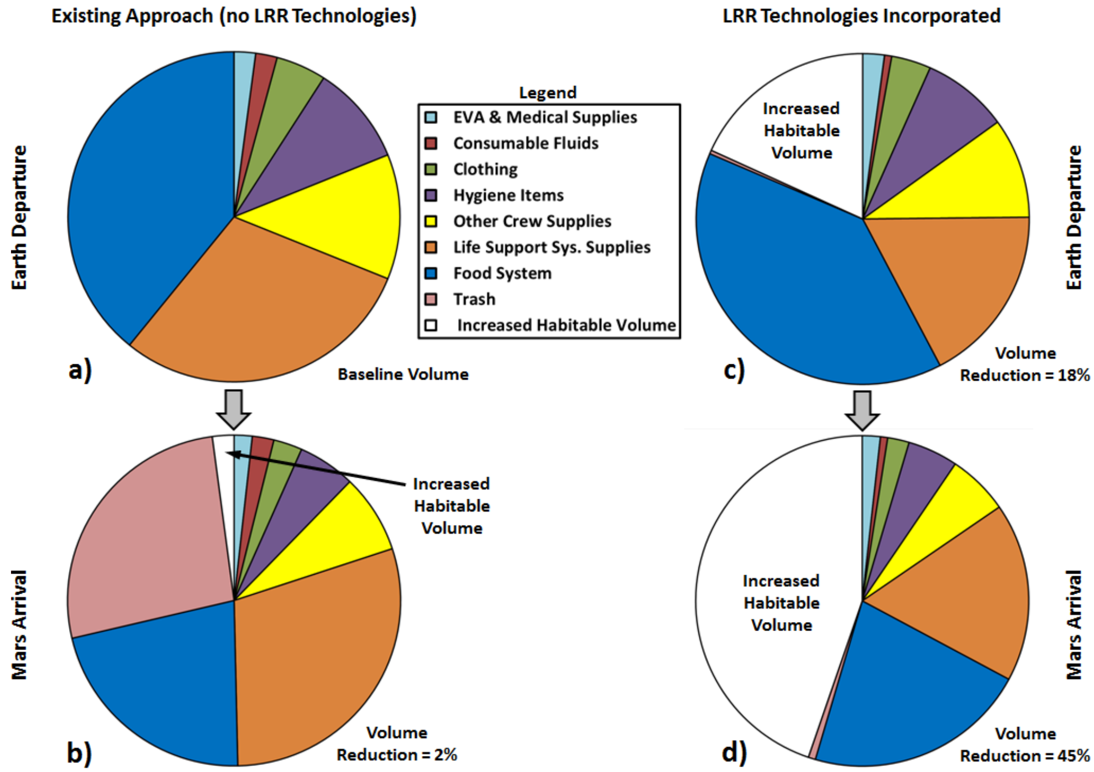


Figure 10. Volume comparison of a Mars transit mission logistics volume using existing technologies (a and b) or LRR technologies (c and d). The top row is the volume at Earth departure. The bottom row is the volume at arrival in orbit around Mars.

IV. Conclusion

The reduction, reuse, and processing of logistics and consumables can reduce the initial volume of supplies that must be launched on exploration missions. Even greater volume savings occur as the mission progresses. Without processing, accumulating trash largely maintains the original logistical volume. Repurposing and processing the trash reduces the trash volume significantly, but there is a multiplying effect because it also reduces the volume of water, radiation shielding, crew outfitting hardware, and possibly propellant that must be launched from Earth. The AES LRR project is demonstrating the feasibility of six technologies that reduce initial logistics and use waste as a resource. Analysis has shown 12.8 m^3 of volume savings for the one-way trip to Mars, but the technologies will also benefit the return trip. This volume savings provides mission planners several options. The volume savings can be applied to one or more existing habitation challenges, including increase in the habitable volume, and allowance for additional crew health or science equipment, or it could be turned into additional mass savings by reducing the pressure shell dimensions. Furthermore, some or all of these technologies can also be applied to the Mars surface habitat and other human exploration vehicles and habitats. The LRR technologies will continue to be developed for the next 3 years under NASA's AES program. To aid in technology roadmap and investment decisions, LRR will perform higher fidelity system analyses as missions develop to ensure their integration into future vehicles.

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