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Exploration Mission Benefits From Logistics Reduction Technologies

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Technologies that reduce logistical mass, volume, and the crew time dedicated to logistics management become more important as exploration missions extend farther from the Earth. Even a modest reduction in logical mass can have a significant impact because it also reduces the packing burden. NASA's Advanced Exploration Systems' Logistics Reduction Project is developing technologies that can directly reduce the mass and volume of crew clothing and metabolic waste collection. Also, NASA has developed cargo bags that can be reconfigured for crew outfitting. Trash processing technologies that will increase habitable volume and improve protection against solar storm events are under development. Additionally, Mars-class missions are sufficiently distant that even logistics management without resupply can be problematic due to the communication time delay with Earth. Although exploration vehicles are launched with all consumables and logistics in a defined configuration, the configuration continually changes as the mission progresses. Traditionally, significant ground and crew time has been required to understand the evolving configuration and locate misplaced items. The crew will not be able to rely on the ground for logistics localization assistance for key mission events and unplanned contingencies. NASA has been developing a radio frequency identification autonomous logistics management system to reduce crew time for general inventory and enable greater crew self-response to unplanned events when a wide range of items may need to be located in a very short time period. This paper provides a status of the technologies being developed and their benefits for exploration missions.

Nomenclature

ACS	=	Advanced Clothing System
AES	=	Advanced Exploration Systems
CEP	=	Complex Event Processing
CTB	=	Cargo Transfer Bag
COTS	=	commercial off-the-shelf
dBA	=	decibles A-weighted
EM-2	=	Exploration Mission-Two
ft^3	=	cubic foot
Gen2	=	second generation
HMC	=	Heat Melt Compactor
ISS	=	International Space Station
HRP	=	Human Research Program
IMS	=	Inventory Management System
IVA	=	Intravehicular Activity
kg	=	kilogram
LR	=	Logistics Reduction

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MCTB	=	Multi-purpose Cargo Transfer Bag
MPCV	=	Multi-Purpose Crew Vehicle
m^3	=	cubic meter
NASA	=	National Aeronautics and Space Administration
REALM	=	Radio Frequency Identification Enabled Autonomous Logistics Management
RFID	=	radio frequency identification
TtG	=	Trash to Gas
USOS	=	United States Operating Segment
UTAS	=	United Technologies Corporation Aerospace Systems
UWMS	=	Universal Waste Management System

I. Introduction

LOGISTICS for human exploration encompases a wide range of items when considering an entire mission campaign. Logistics consists of consumables, maintenance items, spares, and science provisions that are typically delivered to a crewed spacecraft in bags and tanks whose quantity depends on the length of the mission. This paper focuses on the consumables directly related to the crew members and the packaging of those consumables, which are often defined as crew provisions and do not specifically include life support water and gases. Crew provisions are typically related to the number of crew and duration of each mission phase (e.g., crew days). Crew provisions can also be associated with providing a function (i.e., waste processing or logistics tracking), which may be only indirectly related to crew days. Exploration mission studies are increasingly recognizing the impact of logistics and the importance of logistics usage assumptions and logistics reduction technologies on overall mission architecture.[1,2] The Advanced Exploration Systems (AES) Logistics Reduction (LR) project is developing improved logistics and waste models, as well as five logistics reduction technologies: long-wear clothing, reusable Cargo Transfer Bags (CTBs), trash management, compact metabolic waste collection, and autonomous logistic management technologies. Food is the largest crew provision and is driven by shelf life, packaging, and storage conditions. The Human Research Program (HRP) leads food technology research.[3] However, the AES LR project is currently assisting HRP with trade studies related to water content and cold stowage and will support future HRP publications in this area. The intent of this paper is to provide an overview of the technologies being investigated and how they benefit future exploration missions. For more details on individual technologies, references to specific publications are provided.

II. Logistics and Waste Models and Their Mission Impacts

AES LR has developed logistics and waste models for exploration missions based on International Space Station (ISS) data. The ISS data are adjusted for a four-person crew on a 1-year mission and assumptions on logistics and life support technologies. AES LR has been collaborating on logistics and waste models with the NASA Evolvable Mars Campaign analysis and the NASA Future Capabilities Team studies to establish similar assumptions across mission studies. The basic AES LR model was previously described[4,5]; however, a representative breakout of logistics and waste is provided in Figure 1. The consumable logistics items total 5,500 kg (12,100 lb), with the food system accounting for about half. This mass is eventually converted to solid, liquid and gaseous waste products from the crew. In most cases, like clothing or crew supplies, 'waste' is less than 'logistics' since some of it is still in use at the end of the mission. Nevertheless, 2,600 kg (5,700 lb) and 9 m^3 (320 ft^3) of waste products are still generated and must be approiately managed. The logistics and waste models help identify areas to which technology development funds should be directed. As previously mentioned, HRP addresses food and food packaging; however, AES LR supports their program efforts because food is the largest logistical item. The waste from food appears small because it only represents the residual food adheared to packaging or not eaten. The majority of food mass is metabolically converted to urine, feces, carbon dioxide, and perspiration. Urine and feces are included in the AES Waste model. Carbon dioxide and perspiration are included in AES Life Support System project models. Similarly, the Universal Waste Management System project of AES LR supports the area of life support/consumable fluids. Advanced clothing technology address both clothing resupply and waste. Automated inventory management address other crew supplies and food containers. Waste processing by the Heat Melt Compactor (HMC) addresses all waste areas except feces (addressed by trash to gas [TtG] or fecal torrefaction technologies) and brine (addressed by life support systems). The models (currently on version 2.9) are also used to evaluate the mission benefits of AES LR technologies.

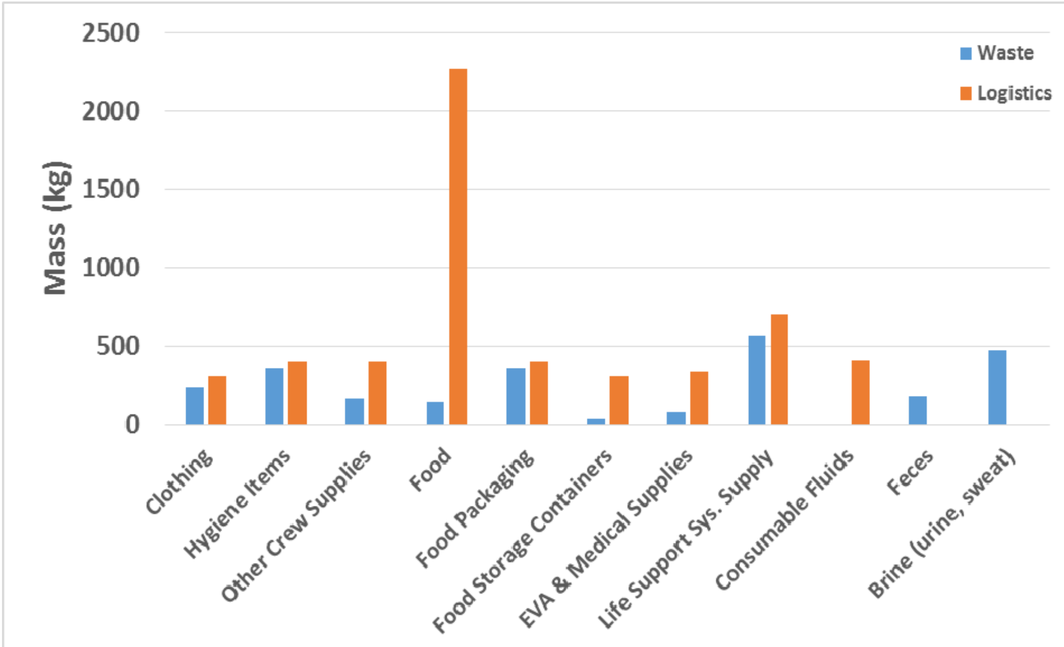


Figure 1. LR crew-related consumables and waste mass for a four-person, 1-year mission.

III. Direct Reduction of Clothing Logistics

Crew members inhabit the ISS for 6 months at a time. Clothing is launched incrementally to sustain the needs of the crew. Space laundry and clothing sanitation systems do not exist on the ISS. Therefore, the clothing is disposed of once it is unacceptable to wear. Thus, clothing accounts for a significant portion of the logistical mass launched on human space missions: 300 kg (662 lb) and 0.73 m^3 (26 ft^3) for a 4 person crew, per year. The mass and volume burden of clothing needs to be reduced for long-duration missions. The Advanced Clothing System (ACS) project of the AES LR focuses on directly reducing cost, up-mass, and disposal burden. These benefits will help enable long-duration missions beyond low Earth orbit.

Crew clothing includes routine-wear shirts, pants, shorts, socks, and underwear. It also includes exercise shirts and shorts. Crew clothing was custom made during the early NASA programs. Currently, crew members are able to select the clothing they want to wear during a mission from a catalog that is developed internal to NASA. The catalog contains mostly commercial off-the-shelf (COTS) items and is updated periodically to reflect changes in the availability of an item or to add new selections. Crew members have influence over which items are included in the catalog; however, safety characteristics such as flammability, toxicity, and off-gasing are all considered. Therefore, the clothing is selected based on comfort and the features (e.g., pockets, zippers, etc.) needed during use in microgravity.

In 2014, the systems engineering team of the LR conducted a trade study[6] to compare the equivalent system mass of laundry systems, sanitation systems, and disposable clothing. The study determined that longer-wear clothing increases the break-even point for laundering vs. disposable clothing sufficiently (~330 days) to delay laundry development until Mars surface missions are planned. The partial gravity of the Mars surface will greatly simplify liquid/gas/clothing phase separation issues that are present in microgravity. Hence, the ACS effort has focused on understanding factors that determine when clothing becomes unacceptable and which fibers can be worn longer based on crew preference.

The ACS project is evaluating lightweight and antimicrobial fabrics used in COTS clothing for extended use during long-duration missions. COTS clothing is evaluated since the private sector has made great advances in performance clothing that NASA can leverage, and it is a more cost-effective option. The goal of the ACS evaluations is to determine which fabrics can extend the life of a garment, thus requiring less clothing for the overall mission. Additionally, since crew clothing is very personal, preference data is essential to determine the acceptance of different types of clothing.

In prior years, the ACS project conducted several studies to collect preference and length-of-wear data. The studies included four mission analog studies: the Multi-Mission Space Exploration Vehicle and the Deep Space Habitat ground experiments to provide exercise T-shirts to their participants; and two Hawai'i Space Exploration Analog and Simulation missions to collect data on exercise clothing and sleepwear. The largest ground evaluation was an 80-participant study to evaluate exercise clothing. The ground evaluation results were used to downselect the garments for the follow-on ISS study and to test the evaluation survey.

In 2014 and 2015, the ACS team developed and conducted an ISS experiment called the Intravehicular Activity (IVA) Clothing Study.[7] The IVA Clothing Study collected data from six crew members on the length of wear and preference of two types of exercise shirts, lightweight exercise shorts, and two types of routine-wear shirts for a 15-day period. The exercise shirts were wool and polyester, the exercise shorts were polyester, and the routine-wear shirts were wool and modacrylic. The exercise clothing component was also duplicated on the ground to determine whether there were any physiological changes due to microgravity that would affect the length of wear or preference. This study was the first human science collaboration with Roscosmos under the restructured Scientific and Technical Advisory Council.[8]

Figure 2. Crew members during IVA Clothing Study experiment on ISS

The study resulted in valuable findings. The length of wear and preference data did not indicate that physiological changes due to microgravity produced any differences between on-orbit and ground data. Therefore, future clothing evaluations can be conducted on the ground. For the exercise clothing component, wool exhibited the longest length of wear for exercise shirts. However, polyester was viewed more favorably by the crew. If wool replaced the current X-static shirts being flown, a mass savings of 36 kg (80 lb) for a four crew one year mission can be realized. For the routine-wear component, modacrylic was the longest length wear in routine shirts and was viewed more favorably than wool. If modacrylic replaced the cotton shirts being flown, a mass savings of 24 kg (52 lb) for a four crew one year mission can be realized. None of the preference parameters (e.g., odor, flexibility, etc.) were predominantly unfavorable before a garment was retired. However, later crew debriefs indicated appearance after extended wear due to staining was a factor in deciding to retire garments. Wool and modacrylic are determined to be valuable additions to the crew clothing catalog. These materials are lighter than the current cotton shirts and can be worn for longer durations. The ACS project will work with the NASA crew provisioning group and crew office to infuse these garments into the crew clothing catalog.

One of the limitations of the IVA Clothing Study is the small sample size and short duration of the study. It provided data that have never been collected. However, it is desirable to have a longer-duration study over multiple ISS increments to increase the sample size and gain a better understanding of usage rates. Another part of the LR project is developing radio frequency identification (RFID) technology to track tagged items aboard the ISS. The ACS team would like to RFID tag crew clothing, identifying the unique garment and not the crew member, to collect usage information. This will help fill a knowledge gap in the actual usage rates of crew clothing, which will enable more accurate estimates of clothing required for long-duration missions. The ACS project supports closure of NASA technology gaps defined in the 2015 NASA Technology Roadmap TA06, *Human Health, Life Support, and Habitation Systems*, specifically: 6.1.4.5 Long Wear Clothing (Advanced Clothing).[9]

IV. Reuse of Cargo Transfer Bags – Impact on Logistics

Crew provisions and maintenance spares for the ISS are launched in CTBs, and will be launched this way on future exploration missions,. CTBs come in several different sizes and are based on variations of a "single" suitcase-like size of 50.2-cm (19.7 in.) long x 42.5-cm (16.7 in.) wide x 24.8-cm (9.8 in.) high. Standard CTBs are available in half, single, double, and triple sizes with empty weights of 1.0 kg (2.2 lb) to 2.8 kg (6.1 lb). CTBs protect interior cargo with the help of packaging foam and must maintain their shape and structural integrity under launch loads while strapped to the launch vehicle. On orbit, they help organize logistics until use, are sometimes used for trash storage, and become trash themselves. As many as 170 CTBs would be required for a 1-year mission of four crew members.

The Multi-purpose Cargo Transfer Bag (MCTB) project of AES LR is developing CTBs that can provide their launch function and then unfold into flat sheets and be used for secondary crew outfitting. The MCTB is configured as a bag using zippers and/or snaps. The manual release of the zippers and snaps allows the bag to assume its flat configuration. The range of MCTB concepts include solar radiation storm shelters, lightweight crew quarters, water processing partitions, and acoustic absorption.[10] The secondary purpose of the MCTB should be known in advance so specific features for attachments, pass throughs, and materials can be incorporated. The MCTB goal is that reusing the cargo bag reduces the amount of secondary structure and blankets that must be flown. This results in less overall vehicle mass and a near-zero-trash cargo bag because the bag was not thrown away after unpacking. One operational challenges for MCTBs is that a limited number of bags are unpacked at the beginning of the mission. The remainder of the bags get unpacked as the mission progresses. Therefore, careful planning of the use of MCTBs for crew outfitting is required to balance between when the outfitting is desired and when the MCTB contents are needed in the mission.

In 2015, AES worked with the ISS Acoustics Office to develop acoustic mitigation for the ISS exercise treadmill using MCTBs rather than dedicated acoustic blankets. The treadmill noise at high speeds was exceeding 85 dBA levels and requiring the crew to wear hearing protection during exercise. Acoustic modeling and acoustic transmission material testing performed by the ISS Acoustics Office showed a potential 2 to 3 dBA reduction at the head position of the crew member when two walls near the treadmill were covered with a dual layer of “Acoustic” MCTBs. The Acoustic MCTBs are comprised of a four-material layup tailored to the frequencies of interest. The details of MCTB construction and function will be addressed in a separate future paper after they have been evaluated on orbit for several months. In addition to the on-orbit acoustics function, the Acoustic MCTBs also have to support structural launch loads for the cargo when it is a bag. This required structural loads testing of the bag folds, zippers, and snaps to restrain the launch acceleration of the cargo mass. Several modifications of the original design were required until an acceptable configuration was determined. Four double Acoustic MCTBs were designed, prototyped, structurally tested, and certified in 7 months. The four acoustic MCTBs were delivered in July, 2015, and packed with mission hardware, as was a normal CTB. The hardware was successfully launched on Orbital flight 4 in December 2015. The Acoustic MCTBs will be installed on the wall immediately behind the treadmill and to the runner’s right (Figure 3). Previously, both of these solid surfaces acted as sounding boards for the treadmill noise. When the MCTBs are installed in mid-2016, the crew will take acoustic measurements to verify the treadmill noise was reduced to validate engineering modeling.

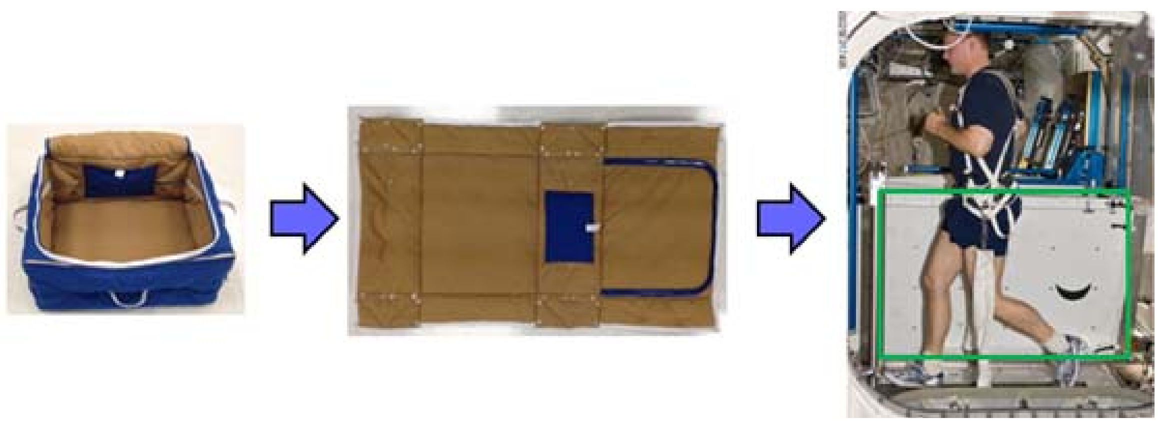


Figure 3. Repurposing of MCTB for mounting on the ISS Waste and Hygiene Compartment wall to mitigate treadmill acoustic noise.

From an exploration perspective, the benefit is the reduction in mass of not having to launch dedicated acoustic blankets in two regular double CTBs. This saved approximately 4.1 kg (9 lb) of mass and ~0.02 m^3 (0.7 ft^3) of volume for only this one application. Additionally, when the acoustic MCTBs eventually become soiled and need to be replaced, they can be reconfigured into their original bag configuration and be used to store other vehicle trash. Approximately 170 CTB equivalents are required for a 1-year mission with crew of four. It is estimated that approximately half of these could be repurposed into crew quarters, partitions, and crew outfitting, potentially saving 140 kg (309 lb) and 0.5 m^3 (17.6 ft^3) The MCTB technology supports closure of NASA technology gaps defined in the 2015 NASA Technology Roadmap TA06, *Human Health, Life Support, and Habitation Systems,*[9], and TA07, *Human Exploration Destination Systems*, specifically: TA 06.1.4.2 Multi-Purpose Cargo Transfer Bag.[11]

V. Processing of Trash – Impacts on Logistics

The ISS trash is often manually compressed into small bags and wrapped with duct tap, often referred to as a football. Footballing of trash can reduce its volume by approximately 2:1. On the ISS, trash footballs and other trash are collected and placed in a variety of larger bags depending on whether the trash is dry or wet. The trash bags are placed in visiting logistics vehicles for disposal. These visiting vehicles depart approximately every 2 months. There currently is no trash processing onboard the ISS to substantially reduce trash volume, microbially stabilize it to prevent odors, or recover water.

As described in Section II, for a 1-year crew-of-four mission, approximately 2600 kg (5730 lb) and 9 m^3 (318 ft^3) of waste is generated. This represents a substantial mass and volume that must either be disposed of periodically, as done on ISS, or stored on long transits where there may not be a vehicle element disposal for more than 6 months. Trash stored at the ambient conditions present in a spacecraft will generate odors. If the trash contains moisture and residual food, then microbial proliferation will occur and odor/gas generation can substantially increase. Generated gas is generally not contained in the trash bag, and either permeates the bag material or the bag must contain an adsorber material – i.e., activated charcoal. Trash processing can provide substantial mission benefits for missions where resupply and disposal options are infrequent. Trash processing ranges from simple trash drying, to moderate heating and compaction, to high-temperate thermo-chemical decomposition of the trash. Trash drying will slow odor generation and microbial proliferation, and will recover water. Heat Melt Compactor (HMC) technology provides moderate heating and compaction. HMC can microbially stabilize the trash, recover the water, and provide volume reductions of greater than 7:1. The resulting compact tile can be stored, used for radiation shielding, or jettisoned. High-temperature thermal processing (referred to as TtG), microbially stabilizes the trash, generally does not recover the water, and provides a volume reduction of approximately 10:1. The gas is jettisoned by venting.[12] Jettison of trash either by periodically ejecting HMC tiles or by venting of TtG not only eliminates the trash but can save vehicle propellant because the overall vehicle mass is reduced during thrust operations. The NASA Evolvable Mars Campaign team is currently analyzing the benefits of trash jettison.

The AES LR project has previously investigated TtG and evaluated seven different technologies, including subscale processing of representative trash.[13,14] Steam reforming was determined to likely be the best technology if maximum methane production was the goal. Pyrolysis was determined to likely be the best technology if no particular gas was desired. TtG technology development is currently on hold; however, it may be restarted in the future to meet identified mission needs.

The AES LR project has been actively investigating HMC technology. Numerous detailed papers have described the HMC development.[15-18] HMC basically consists of placing trash in a compaction chamber. The chamber pressure is then reduced and the temperature is raised to approximately 160°C (320°F). This boils off the moisture, which is carried away by low flow rate of carrier gas where it is condensed for recovery. The elevated temperature softens the plastic items in the trash and compaction forces drive the softened plastic around the non-meltable trash. The compacted state is held while the chamber is cooled, resulting in a relatively rigid dry tile of trash that is microbially stable. The trash tile can simply be stored. However, its chemical makeup contains approximately 8% hydrogen by mass, due mostly to the original plastic, fabric, and foam materials in the trash. This is comparable to the 11% hydrogen content of water. Hence, there is interest in using it for radiation shielding on long missions. Testing of the early HMC tiles shows it has a shielding effectiveness of 91% of solid high-molecular-weight polyethylene.[19] Technical challenges for HMC must be addressed to take advantage of these benefits. These challenges include improved thermal performance, control of caramelized organics in gas passages, and, most significantly, control of evolved gases during processing. The elevated temperatures drive off volatile organics from the plastic, food, and packaging foam.[20] HMC is investigating the use of an activated carbon adsorber to remove sulfur compounds and a compact recuperative thermocatylitic reactor to oxidize the hydrocarbons to mostly carbon dioxide. Additional research is also required to understand and characterize the off-gassing of tiles while they are stored.

A full-scale second-generation (Gen2) HMC has been developed (Figure 4). The unit can process approximately 1.6 kg (3.5 lb) of trash into a 23-cm (9-in.) square tile approximately 2.5-cm (0.9-in.) thick. These tiles efficiently pack in a CTB volume or can be placed in overlapping sheets to provide walls for a solar radiation storm shelter. The Gen2 HMC was fabricated in 2014, assembled in 2015, and followed by a checkout of the components and subsystems. A design issue with the compaction mechanism was discovered and is in the process of being evaluated, therefore characterization testing has not yet occurred. This Gen2 HMC will be used, as program resources allow, to finalize process parameters using ground tests. These results will be used to develop a unit for an ISS technology demonstration.

For exploration, HMC has the potential to process more than 1200 kg (2,636 lb) of waste for a 1-year, four-person crew. It is estimated that HMC could recover approximately 8 m^3 (283 ft^3) of habitable volume by reducing the trash volume. Additionally, HMC could produce more than 900 kg (1,984 lb) of radiation shielding tiles and recover 230 kg (507 lb) of water. These tiles are produced over the duration of the mission, so logistics mass is required for radiation shielding for the initial shielding. As logistics are consumed the tile mass replaces it in a more dense form. For Mars surface operations, HMC tiles are microbially inactive and can contribute to planetary protection plans. The HMC technology supports closure of NASA technology gaps defined in the 2015 NASA Technology Roadmap TA06, *Human Health, Life Support, and Habitation Systems*, specifically 6.1.2.2 Trash Management.[9]

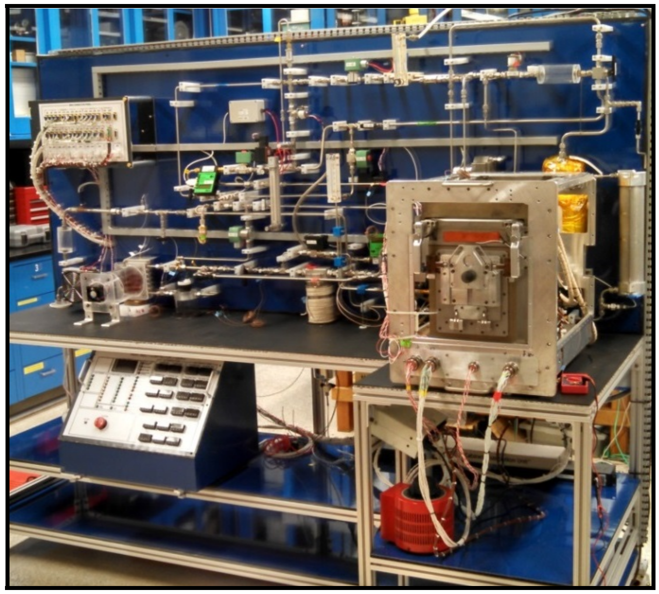


Figure 4. The HMC core unit, the water recovery system, and the trace contaminant control system prior to insulation.

VI. Improvements in Metabolic Waste Collection to Reduce Logistics

Future exploration vehicles being developed by NASA have smaller habitable volumes than the ISS and Space Shuttle. As habitable volumes decrease, vehicle systems must also decrease in size to accommodate crew members. Metabolic waste systems are critical to crewed missions. The waste collection systems designed for microgravity collect urine from the crew via a funnel with airflow that aids in collection.[21] The urine continues on to a rotary separator where the liquid and air are separated. The air will return back into the cabin through a charcoal filter system. The liquid will either be collected for disposal or be delivered to a urine processing system for water reclamation. The solid waste is collected with airflow aiding in odor control and capture. The solid waste is stored for disposal. In addition to collection of metabolic waste, hygiene and ease of use of the system for both male and female crew members is a major component of waste collection system design. Due to anatomy and the difficulty for many females to separate urine and solid waste functions, the seat and funnel on the system must be designed to improve the ability to align the funnel properly with the body. This is a particular challenge that needs to be better addressed in future waste collection system designs.

Past systems have been designed for either short-duration or long-duration use. For the Space Shuttle missions, the urine was vented periodically and the solid waste was collected in a permanent tank that was refurbished once on the ground. The ISS currently has two systems developed by Russia’s Rocket and Space Corporation Energia that are virtually identical; one in the Russian segment and one in the United States Operating Segment (USOS). In the USOS Waste and Hygiene Compartment, the urine is delivered into the Urine Processor Assembly for water recovery. The solid waste is collected in canisters that are changed out as soon as they are full. Urine requires chemical stabilization to prevent solids from forming. Strong oxidants are used for long-duration systems where the urine is processed to recover water since solids precipitation and bacterial growth have to be prevented over long periods of time. A more compact waste collection system is needed for smaller exploration vehicles. A system that is compatible with both short-duration and long-duration missions is desired.

The Universal Waste Management System (UWMS) project of AES LR is developing a compact metabolic waste collection system, urine pretreat dose pump to enable water recovery, pretreat quality sensor to monitor the amount of

Figure 5. UWMS ground prototype.

pretreat being delivered by the dose pump, and integration hardware to interface with the ISS. The UWMS is based on the Extended Duration Orbiter Waste Collection System that was developed by United Technologies Corporation Aerospace Systems (UTAS) and flown on the Space Shuttle four times.[21] The UWMS leverages that design and improves upon it to reduce the mass and volume; increase crew comfort and performance, particularly for female simultaneous urination and defecation; and enable urine processing.[22] The compact design is enabled by three key features: dual fan/rotary separator with a single motor driving two fans and the urine separator[23]; shortened fecal transport tube and collection bag; and odor bacteria filter integrated within the structure.

The UWMS provides a significant installed hardware volume and mass reduction compared to the toilet in the ISS Waste and Hygiene Compartment. The UWMS consumables and replacement hardware can be used by multiple vehicles, thus reducing overall integrated mission logistics complexity.

The UWMS, dose pump, and pretreat quality sensor is developed by UTAS and flown on the ISS as a technology demonstration payload. The ISS integration hardware is developed by NASA and includes structural attachment, fluid transfer, data acquisition, and power hardware to protect against excess electrical current that will enable the UWMS to integrate into the existing systems on the ISS. A second UWMS unit is also being procured for use on the Multi-Purpose Crew Vehicle (MPCV) Exploration Mission-Two (EM-2). The ISS technology demonstration and MPCV EM-2 will demonstrate the performance of the UWMS in long- and short-duration missions.

The UWMS project is in the initial stages of development. The contract for procurement of two UWMS units, dose pump, and pretreat quality sensor was awarded to UTAS in November 2015. The NASA team began development of the ISS integration hardware in January 2016. The hardware will be developed over the next 2 years and delivered in April 2018. The ISS technology demonstration is planned for early 2019 and the EM-2 will launch no later than 2023. The UWMS technology supports closure of NASA technology gaps defined in the 2015 NASA Technology Roadmap TA06, *Human Health, Life Support, and Habitation Systems*, specifically 6.1.3.1 Metabolic Waste Management.[9]

VII. Improved Logistics Tracking – Impact on Logistics

Logistics tracking in space is currently based on manually scannable barcodes on items large enough to be tagged. On the ISS, this represents more than 45,000 items that were delivered over many missions and likely relocated by the crew several times to consolidate logistics as they are used. Crew rotations occur approximately every 6 months on the ISS, thus it is likely the current crew is looking for something relocated on orbit by a prior crew. Despite periodic inventory surveys and crew call downs, inventory location and quantity accuracy deteriorates over time despite the best efforts of the ground and crew. The current repository of ISS inventory is the Inventory Management System (IMS), which is maintained on the ground. The ISS is the volume of a five-bedroom house. If an item is not actually in the IMS-indicated location, finding it can require a significant amount of crew time, which delays planned activities. Returning ISS crews indicate that a substantial amount of time is spent on looking for items needed 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[24] and the current estimated rate for crew time.

Efforts are underway to implement improved ISS IMS labels that incorporate RFID chips and antennas. In 2014, the ISS began using RFID tags on common consumables with the goal to eventually have almost all items use the new tags. The objective is to have RFID Enabled Autonomous Logistics Management (REALM) on future exploration vehicles and use the ISS to determine the required architecture. The goal of REALM is to be able to use RFID readers to automatically record not only the presence of an item, but also its location. REALM can use multiple antennas and read the IMS RFID tag return signal strength and essentially triangulate the general location of an item. Basic RFID technology is already used terrestrially for a range of simple tasks such as store security tags, car toll tags, and limited warehouse logistics tracking at the pallet level. However, terrestrial applications generally involve low tag densities, large physical volumes, and implementation of a few neck-down locations for reading. Space vehicles represent a unique and new challenge for RFID technologies, including the desire to rely only on passive tags, restrictions on RF transmit power, layered storage of logistics, the challenging RF scattering environment of vehicles, and metallic storage enclosures. To address this complex problem, associated RFID technologies are partitioned into three classes and are being developed as part of three corresponding AES LR REALM projects.[25,26]

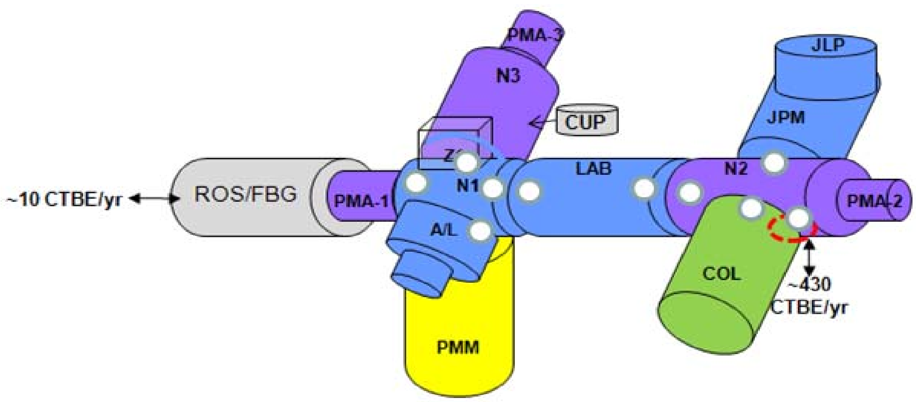
- Complex event processing (CEP) (Being developed as part of REALM-1)
- Sparse zone technologies (REALM-1 fixed systems, REALM-2 mobile system)

- Dense zone technologies (REALM-3)

Dense Zone technologies (REALM-3) pertain to enclosures with conductive, or shielded, boundaries and an integrated RFID reader to interrogate the items contained within. Sparse zone technologies address all areas, except for dense zones, including the open areas of a habitat module and in cracks or crevices, such as behind a rack. These technologies include fixed zone readers (REALM-1), steered-beam-antenna readers, and mobile readers such as robotic elements (REALM-2), crew-held readers, or crew-worn readers. With both dense and sparse zones, guaranteed real-time on-demand reads are not possible, therefore “smart” applications or CEP is required to infer item locations based on context from the sparse and dense zone technologies and how relationships are maintained over time.

Figure 6. REALM-1 flight-like RFID reader connects to four custom antennas. A total of six readers and 24 antennas are planned.

AES LR has nearly completed hardware development for REALM-1 (Figure 6). REALM-1 consists of RFID hatch readers and CEP to localize items within one-half to one element module on the ISS. It will provide the core infrastructure for a modular REALM architecture. The hatch readers and CEP provide basic logistics awareness in the effort referred to as REALM-1. NASA will develop REALM-1 in collaboration with the University of Massachusetts, Amherst, and it will be evaluated on the ISS with RFID hatch readers and antennas deployed in ISS Node 1, U.S. Laboratory, and Node 2 (Figure 7). A ground-based CEP center will receive data from the ISS hatch readers and will provide operational intelligence that infers item locations.



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

For exploration, implementation of REALM will free up crew time for science, increase autonomy, and reduce reliance on the ground for inventory management. This will be particularly important for Mars transit and surface missions when round-trip communication time can be 44 minutes. Quickly finding something in response to an unexpected anomaly will demand immediate localization of inventory items that REALM will be able to provide. REALM’s RFID network of readers is essentially a low power distribution and communication network. Exploration missions with REALM technology will be able to broadly use wireless sensors that harvest power from the RFID signal and report the sensors’ data to REALM. This should result in significantly reduced sensor cable mass. In addition to crew time, there is a direct physical benefit from REALM technologies. Assured localization of assets can enable heterogeneous packing to optimize volume efficiency, rather than packaging, to increase crew-time efficiency (which is done for the ISS). Currently, foam is used to fill small voids in homogeneous packed items to facilitate reliable crew access to items.[16] REALM can allow rapid location of items in densely packed CTBs that could reduce foam usage in logistics packaging by up to 50%. Packaging foam represents up to 30% of ISS cargo volume so the improvement for exploration can be significant because that also means fewer CTBs are required. The net effect is a savings of approximately 90 kg (198 lb) for a 1-year, four-person crew. AES LR is also collaborating with industry to develop advanced six-degree-of-freedom RFID-infrared-based sensors that can provide centimeter-level accuracy and orientation.[27] The advanced RFID-IR technology has potential for robotic precursor missions by enabling machine interaction with logistics, including packing and assembly functions in advance of crew arrival. The REALM technology supports closure of NASA technology gaps defined in the 2015 NASA Technology Roadmap TA06, *Human Health, Life Support, and Habitation Systems*,[9] and TA07, *Human Exploration Destination Systems*,[11] specifically: 6.3.1.6 RFID based Medical Inventory Tracking Hardware and Software, 7.2.1.3 Power Scavenged Wireless Sensor Tag Systems, 7.2.1.4 Dense Zone Technology, 7.2.1.5 Sparse Zone Technology, 7.2.1.6 Logistics Complex Event Processing, and 7.2.1.7 Six Degrees of Freedom Logistics Tag System.

VIII. Conclusion

Logistics mass and volume must be reduced for exploration missions beyond low Earth orbit. Direct logistics reduction (ACS and UWMS), reuse of logistical packaging (MCTBs), processing of logistical waste (HMC and TtG), and accurate tracking of logistics (REALM) show significant mass saving contributions to exploration missions. These benefits are still being investigated for their integrated vehicle benefit on vehicle propellant mass savings. Additionally, the crew time savings and enabling of autonomous logistics management by the crew and robotic elements also require additional refinement. The AES Logistics Reduction Project will continue developing these technologies over the next 2 years and provide updates in future publications.

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