Current Logistics Reduction Accomplishments and Plans to Support Exploration Missions

Melissa K. McKinley[1] Michael K. Ewert[2], Melissa A. Borrego[3], Patrick Fink[4]
NASA Johnson Space Center, Houston, Texas 77058

Steven Sepka[5],
NASA Ames Research Center, Mountain View, CA 94035

Management of logistics on exploration missions includes both looking for ways to minimize the quantities, mass, and volume of various consumables, supplies, spares, and equipment as well as ways to minimize the crew time needed for locating and handling those items. Also included are ways to minimize the waste, handling, and resultant products from the processes of maintaining a crew on these missions. The Logistics Reduction portfolio encompasses technologies for management of waste, trash, and autonomous logistics. This paper provides a status of work completed in 2024 in these areas including recent accomplishments and challenges encountered. Future objectives and plans for 2025 will also be covered along with the work currently in progress. Specifically, the paper will cover technologies in waste management, namely, the Universal Waste Management System (UWMS) or exploration toilet and work on an alternative waste collection container, the Alternate Fecal Canister. Trash management technologies work on the Trash Compaction Processing System (TCPS) is summarized with progress to date as well as information on how Jettison as an option is related and studies related to the trash management strategy. Progress and summary of recent accomplishment on the RFID (Radio Frequency ID) Enabled Autonomous Logistics Management (REALM) technology is detailed. Work in the area of Systems Engineering and Integration (SE&I) is also included. Status of the technologies and accomplishments and how the focus areas inform program decisions are summarized.

[1] MCO Logistics Reduction Project Manager, Crew & Thermal Systems Division/Mail Stop EC7.
[2] MCO Logistics Reduction SE&I Lead, Crew & Thermal Systems Division/Mail Stop EC2.
[3] MCO Logistics Reduction Habitation Systems Project Manager, Crew & Thermal Systems Division/Mail Stop EC7.
[4] MCO Logistics Reduction REALM, Avionics Systems Division/Mail Stop EV8.
[5] MCO Logistics Reduction TCPS Lead, Space Biosciences Division/Mail Stop SCB.

Acronyms and Nomenclature

ACS	=	Advanced Clothing System
AM	=	Additive Manufacturing
BAA	=	Broad Agency Agreement (BAA)
BOBs	=	Bulk Overwrap Bags
CEP	=	Complex Event Processing
CHAPEA	=	Crew Health And Performance Exploration Analog
CTB	=	Cargo Tranfer Bag
DMS	=	Drawer Monitor System
HLS	=	Human Landing System
HYDRA	=	Hyper-Distributed RFID Antenna
ISS	=	International Space Station
JSC	=	Johnson Space Center
LOO	=	Lavatory On-Orbit
LR	=	Logistics Reduction
M2M	=	Moon to Mars
MCO	=	Mars Campaign Office
ML	=	Machine Learning
NASA	=	National Aeronautics and Space Administration
NextSTEP	=	Next Space Technologies for Exploration Partnership
REALM	=	Radio Frequency Identification Enabled Autonomous Logistics Management
RF	=	Radio Frequency
RFID	=	Radio Frequency Identification
SBIR	=	Small Business Innovation Research
SE&I	=	Systems Engineering and Integration
STTR	=	Small Business Technology Transfer
TCPS	=	Trash Compaction Processing System
TIH	=	Toilet Integration Hardware
TRL	=	Technology Readiness Level
UWMS	=	Universal Waste Management System
WSTF	=	White Sands Test Facility
ZSR	=	Zero-Gravity Stowage Rack

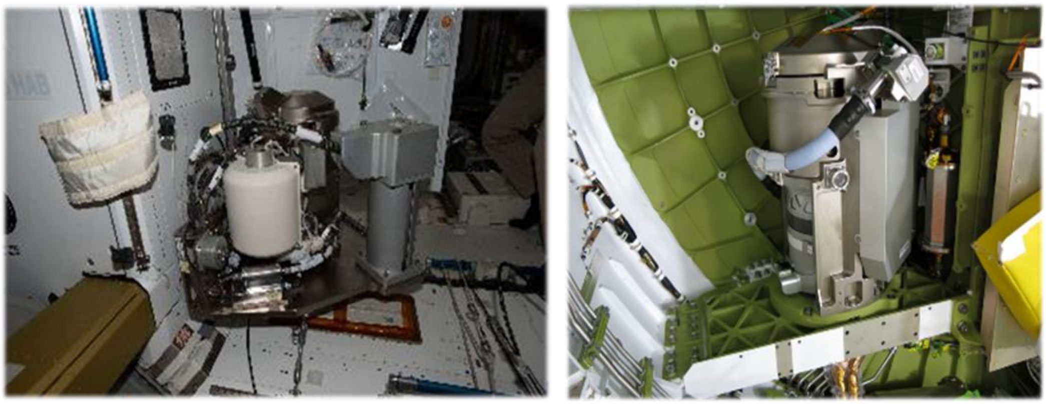
I. Introduction

Technologies for reducing crew consumable mass, reducing crew time for logistics management, and managing trash are being developed by the Mars Campaign Office (MCO) Logistics Reduction (LR) portfolio. In addition to reducing mass, volume, and crew time, it is important that technology developments directly address exploration technology gaps[1,2] which focus on enabling exploration missions to Mars. This is done using a range of government and industry collaborations to enable the space economy. It is equally important that technologies have paths that lead to validation as an International Space Station (ISS) technology demonstration (or suitable ground analog) prior to implementation into exploration architectures to allow demonstration in a microgravity environment.

The MCO LR portfolio scope includes technology areas that primarily target crew consumables, logistics management, and waste management. This paper summarizes technology development progress over the past year and provides references to papers with additional details. Logistics management via direct mass reduction is being investigated with longer wear crew clothing, compact toilets, fecal waste container optimization of mass and volume, and on-demand manufacturing in lieu of dedicated logistical spares and item reuse or repurposing (e. g. laundering crew clothing and cargo transfer bag reconfiguration for habitat outfitting). Some logistics and waste products can be processed, and the products used for a secondary purpose, which prevents the need of launching the secondary item. This includes processing of fecal material and trash to recover water. Processed trash can also supplement vehicle radiation shielding, and in-space manufacturing has the capability to convert broken items into manufacturing feedstock. Additionally, trash can be thermally deconstructed to gas and vented or cleaned up and used. Crew time is very valuable for both short-term and longer missions. Autonomous tracking of cargo saves crew inventory time, helps find lost items, and facilitates denser packing. Autonomous manipulation of cargo using robotics can occur prior to crew arrival, during crewed periods, and after the crew departs, thereby allowing the crew to focus on science and critical vehicle maintenance.

II. Metabolic Waste Collection Technologies

A new toilet was developed for use on long range exploration missions with the purpose of reducing mass and volume and improving hygienic use for male and female crew members. The project provides two units; one which will be demonstrated and evaluated on ISS and one to fly on the Orion Artemis II mission. This toilet, the Universal Waste Management System (UWMS), builds on technologies used on Shuttle flights as well as technologies currently in use on ISS.[3] The Orion UWMS was delivered to Kennedy Space Center on December 23, 2019 and was installed into the Artemis II vehicle in March of 2021. The ISS unit was delivered in June 2020 and launched to ISS in October of that year along with Toilet Integration Hardware (TIH). The Toilet System, which includes the UWMS and the TIH, was installed in December 2020 and a limited checkout was completed in November 2021 on ISS (Figure 1).



a) b)

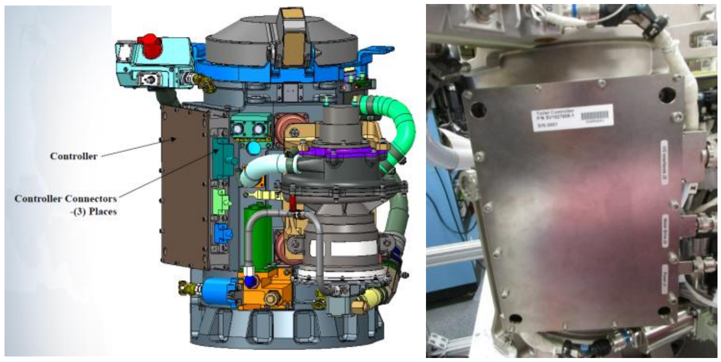
Figure 1. a) UWMS, ISS unit in Node 3 of ISS and b) Orion unit installed in Artemis II (right).

The UWMS collects urine and feces and allows for removal of these wastes for further recycling of urine (ISS unit) or urine venting (Orion unit) and remote storage of the collected fecal material. Both UWMS units rely on a dual fan separator to remove air from the urine stream and to provide air suction to aid in collection of both urine and fecal material. The dual fan separator utilizes a common motor for two fans and the liquid separator to reduce volume and mass. Hard-sided canisters with separate lids were designed to store approximately 20 fecal deposits. Additional details on the excavation of a hard-sided fecal canister filled during the ISS UWMS Limited Checkout and returned to the ground for evaluation are provided in McKinley, et al. (ICES-2024-070.)[4] The capacity of the fecal canister for this demonstration was shown to be 13 deposits.

Completion of a technology demonstration on ISS is currently pending resolution of technical issues with the hardware. A second attempt was made to complete the Artemis II demonstration on ISS in May 2024. More information on the technical issues can be found in referenced papers.[2,3,4] Because the technical issue of the failure of the dose pump to dispense (discovered in 2023) is currently being addressed by a redesign, a spare dosing assembly using the original design was flown to ISS. The expectation was that the reduced exposure to the pretreat solution would result in less damaged PEEK parts and thus decrease the likelihood of repeating the original failure (Figure 2). However, during the check out period, the spare dosing assembly failed to dispense pretreat. Attempts to perform on-orbit troubleshooting showed evidence that pretreat was present in the tank; however, it was not dispensing properly from the pump. Further

Figure 2. UWMS Spare Dosing Assembly.

attempts to perform additional troubleshooting were stymied when the UWMS failed to start on July 5, 2024. A pressure sensor fault which shut down the UWMS was indicated. Repeated attempt to restart were not successful. Operations to evaluate the fault isolated the issue to the controller rather than to a sensor or other effector as the cause. The controller was returned to the ground on Crew-8 for further evaluation (see Figure 3). The failure investigation found the root cause to be a capacitor in the pressure sensor circuit. The capacitor had a void introduced in the manufacturing process, which was exacerbated by installation and powered usage. The crack allowed dendritic growth and consequent fault of the circuit and the system. Investigation of the failure and plans for replacement are still in progress.



a) b)

Figure 3. a) and b). Controller location on UWMS.

Considering crew feedback from the aborted Artemis II Demonstration on ISS (evaluation of UWMS meant to mimic the length and crew size of the Artemis-2 mission) and previous uses of UWMS, the seat and fecal bag for UWMS was redesigned based on early designs for the Human Landing System (HLS) Lavatory On-Orbit (LOO) project.[5] The seat allows the fecal bag to be installed over the seat so it can contact the body during use, see Figure 4. The fecal bag is a smaller volume and has a more crew-accessible closure method. The hardware was delivered in 2023 and an evaluation with UWMS on ISS was performed in June 2024. Qualitative results provided by the crew member showed that air flow was greater for the Grooved Seat with Tube with the updated fecal bag design. Further consensus from the crew office was provided and these updated designs are in work for use on Artemis II. No actual crew use has been performed due to other technical issues with UWMS.

a) b) c) d)

Figure 4. a) Russian WHC use with fecal bag, b) Orion UWMS with original 5" seat and original UWMS fecal bag installed, c) LOO seat design with fecal bag installed, d) Updated seat with updated fecal bag (design #2).

Work continued in 2024 for selection of a replacement gasket to seal between the Alternate Fecal Canister (AFC) and Hard-sided Fecal Canister (HFC) and the odor bacteria filter lid. The original open-cell BISCO gasket allowed odor to escape, causing the hardware to fail odor testing at White Sands Test Facility (WSTF). Testing with two hybrid open/closed cell foams, two closed cell foams and a solid material were not successful and additional materials including a silicon foam, a Viton foam and a Kynar foam are in preparation for additional testing. Updates regarding these efforts may be provided at ICES 2026.

III. Autonomous Logistics Management Tracking Technologies

A. Overview

Autonomous Logistics Management is recognized as a critical technology with gaps that require closure for NASA's near-term planned lunar surface and longer-term Mars remote outpost missions. NASA began experiments based on Radio Frequency Identification (RFID) technologies to address these gaps beginning in 2017. These experiments, serialized as REALM (RFID-Enabled Autonomous Logistics Management), are detailed in ICES-2024-073[6]. They include open cabin RFID readers and antennas to track cargo through vehicle nodes or modules (REALM-1), a robotic-borne RFID reader/antenna system (REALM-2), and a stowage rack-integrated antenna system (REALM-3 *Smart Stow*). All raw data is downlinked to the ground where it is reduced using a set of machine learning algorithms integrated into a Complex Event Processing (CEP) system. In addition, a Drawer Monitor System (DMS) experiment is also flying on the ISS. The DMS is based on special RFID tags with integrated 3-axis accelerometers that serve as motion sensors. The DMS system provides information on when rack doors are open and closed, which provides additional context for the CEP system.

Currently, for near-term remote outpost missions on the lunar surface, audit accuracy and localization accuracy are the focus. The uncertainty in the prevalence of robotic elements in early lunar missions has resulted in a lower priority for robotic-borne RFID systems at this time. Similarly, although DMS is seen as promising and has been proven as a capable sensing system, the Machine Learning (ML) improvement of localization inferences, based on consumption of the additional provided context, remains a low technology readiness level (TRL). The DMS system is sufficiently low mass and low integration complexity, requiring only the placement of relocatable wireless sensor tags, that it could be added to lunar manifests at a later stage once the higher TRL has been demonstrated. Therefore, advances in Smart Stow, and more expanded use of the underlying reader-agnostic multiplexer technology, HYDRA (Hyper-Distributed RFID Antenna), form the strategic basis to close the remaining performance gaps. Results from Smart Stow are addressed in Section B, along with lessons learned applicable to general stowage in conjunction with RFID systems. In Section C, HYDRA technology and the planned ISS HYDRA experiments are discussed.

B. Smart Stow

Smart Stow is an RFID antenna system embedded behind the textile shelf liners of a NASA zero-gravity stowage rack (ZSR). Figure 5 shows the 4-quadrant rack in the background, just after assembly and prior to the attachment of the soft doors. Each quadrant has three shelves, and RFID antennas are positioned behind the liner on the side and back walls, a total of six in each quadrant of the rack. Figure 6 reveals the electronics and antennas behind the liner in a single quadrant.

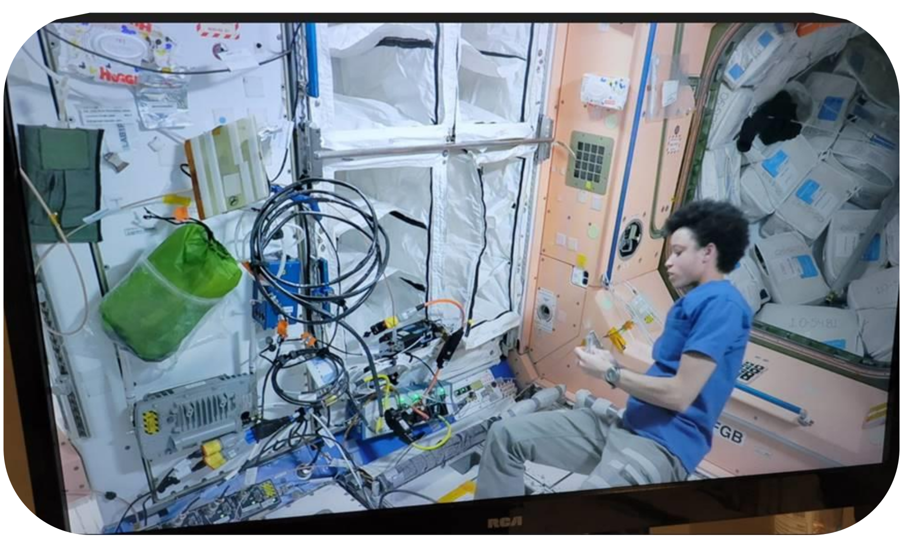


Figure 5. Smart Stow in a Zero-Gravity Stowage Rack (ZSR)

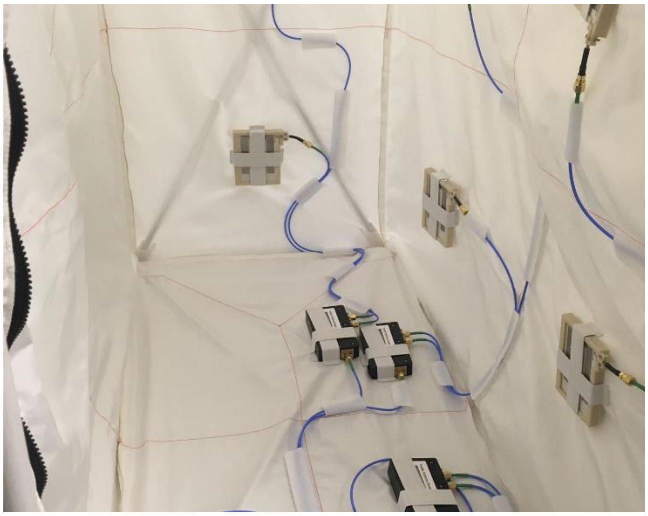


Figure 6. Smart Stow HYDRA nodes and antennas.

The antenna system in Smart Stow is referred to as HYDRA. HYDRA is a reader-agnostic, switched multiplexer antenna system that connects to an RF port of a reader and powers itself by harvesting a small fraction of the incident RFID signal to run an internal microcontroller and switch. Each HYDRA node can connect to other HYDRA nodes or to antennas, all of which are switched so that only one antenna is active at any time. In the combined four quadrants of Smart Stow, HYDRA contains 24 antennas, the same as the entire REALM-1 constellation in 3 ISS modules. In Figure 6, the black boxes are referred to as HYDRA nodes, which similar in cross-sectional size to a smart phone and about twice as thick. HYDRA nodes have a single RF input and multiple RF outputs. In Smart Stow, the nodes have either 3 or 4 output ports. Output ports can be connected to other HYDRA nodes (daisy-chained) or to antennas. More capable HYDRA nodes, discussed in Section C, have 6 or 12 output ports.

Smart Stow has significantly improved the audit accuracy for items stowed in the ISS NOD1S4 ZSR. This ZSR has been exceptionally challenging for RFID audits owing to the contents, called Bulk Overwrap Bags (BOBs), which are aggregations of food packets. The foil liner of the food packets is largely opaque to RFID signals. Figure 7 shows food BOBs in two quadrants of the NOD1S4 ZSR.

Figure 7. Two quadrants of ISS ZSR with BOB contents.

Due to limited truth access for tagged contents on ISS, a replica ZSR rack was developed at NASA JSC, with one quadrant of four shown in Figure 8. This ground analog smart stow serves multiple purposes: it allows for insight into which items are likely to be missed in an RFID audit, it allows compilation of audit statistics, and it permits assessment of methods to improve performance. Although the BOBs on ISS each already have two RFID tags, it is conceivable that a third could be added if it results in substantially improved performance. Other performance studies will include training the machine learning algorithms to determine which BOBs are inside of the rack as opposed to outside but nearby. The analog smart stow is populated with a combination of flight-like BOBs (dark green as shown) and mock BOBs, as the ZSR rack structure is not capable of holding more than two flight-like BOBs in each quadrant in a 1-g environment.

The right hand of Figure 8 b) shows a sample of BOB configurations and color coded as to how many of the two tags on each BOB were read: blue-2; yellow-1; and red-0. In this instance, 74 percent of the Smart Stow RFID tags were read, and 94 percent of the BOBs were read (i.e., at last one tag on a BOB was read). These results align fairly closely with overall statistics in both the ground analog and ISS NOD1S4 Smart Stow data.

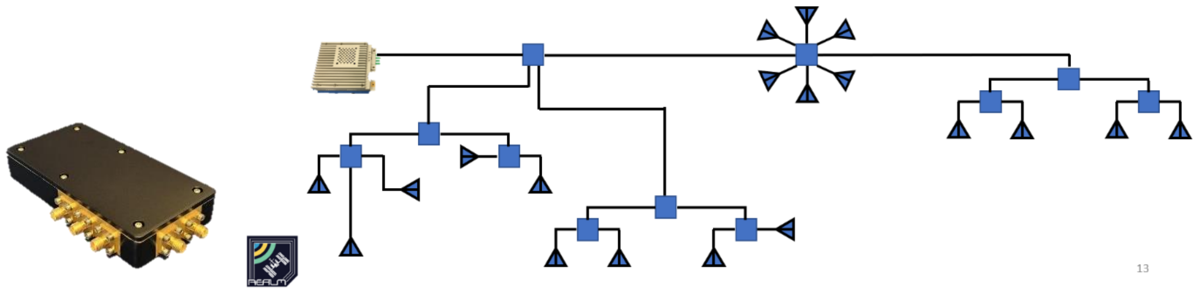
a) b)

Figure 8. a) Ground analog smart stow with mock- and flight-like-BOBs, bottom/top respectively; b) Test configuration of BOBs in 4-rack quadrants: blue: both BOB tags read; yellow: 1 BOB tag read; red: neither BOB tag read.

One conclusion from the REALM-3 Smart Stow study is that double-tagging items is highly beneficial when the items are expected to be stowed densely with a substantial amount of obscuring metal in the environment. Further testing will reveal the point at which there are diminishing returns on additional tags on each item. It is expected that a strategic increase in the order of the contents is likely to improve audit statistics. In the current arrangement, both on-orbit and in the ground analog, the BOBs are stowed without consideration of whether RFID labels get obscured by other items. A scheme in which at least one BOB tag has "visibility" to one of the RFID antennas is likely to provide increased read accuracy.

C. RFID-HYDRA

Owing to the ability of HYDRA technology to greatly proliferate the RFID signal, a new ISS payload, "RFID-HYDRA," is being considered. This payload would greatly expand upon the HYDRA concept such that the HYDRA network would span an entire module with a single reader (Figure 9). Connections between HYDRA nodes comprise only RF cables (i.e., control and power connections are not required). HYDRA nodes have been cascaded successfully in the lab up to five layers deep, theoretically implying the capacity to support over 240,000 switched antennas on a single reader RF port. This greatly exceeds any practical number envisioned for a space vehicle, both for reasons of aggregate mass and switching times (only a single antenna is sampled at any given time on a reader). The former limitation imparts a strong motivation for very low-mass RFID antenna designs, which are in-work. The latter limitation will be a key study in the ISS RFID-HYDRA experiment. It is envisioned that antennas facing into the open cabin region will be sampled frequently during the crew wake period, whereas antennas embedded deep in storage areas are likely to be sample sparingly during crew wake period and more thoroughly during crew sleep. The intent of such a strategy would be to assure that items moved during crew wake are not missed due to a slow sampling rate in the open cabin.



a) b)

Figure 9. a) 1x12 HYDRA node; b) Conceptual layout with daisy-chained HYDRA nodes (squares) and antennas (triangles).

To facilitate the deployment of a large number of antennas by the crew, a textile HYDRA membrane is envisioned. The membrane will support 1 or more HYDRA nodes and 9 to 24 antennas. Key driving requirements for the membrane include low mass and the capability to compress the membrane and attached hardware into a "1.0 Cargo Transfer Bag (CTB)." 1.0 CTBs measure 16"x16"x9". Figure 10 shows a concept for a HYDRA membrane with a 1x12 HYDRA node attached to 9 antennas. The HYDRA membrane will be used behind stowage racks, such as NOD1S4, and behind other stowage regions that have been formed out of recesses and overlying bungee cords to hold contents in place. Deployment of these membranes is expected to facilitate installation by the crew, compared to the more invasive procedure that was required for the installation of Smart Stow.

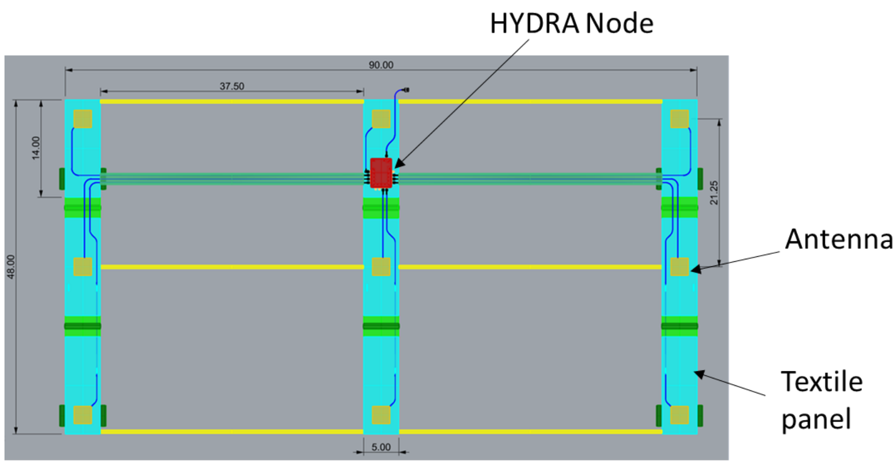


Figure 10. HYDRA membrane with a HYDRA node and 9 antennas.

Figure 11 shows the compacted state of the HYDRA membrane, with coaxial cable shapes imposed by foam tubes to preserve the minimum bend radius. In addition to many antenna embedded behind stowage areas, a lesser number of HYDRA antennas will be directly secured in the open cabin areas in an isolated fashion. Figure 12 shows one of the HYDRA layouts under consideration for ISS. It is tentatively being planned for a launch in the spring of 2026.

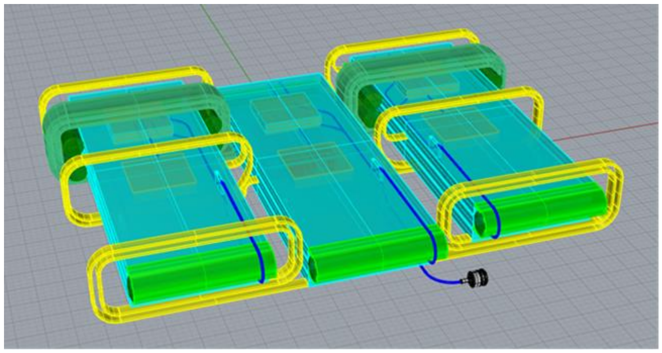


Figure 11. Compacted HYDRA membrane to fit in NASA 1.0-Cargo Transfer Bag (CTB).

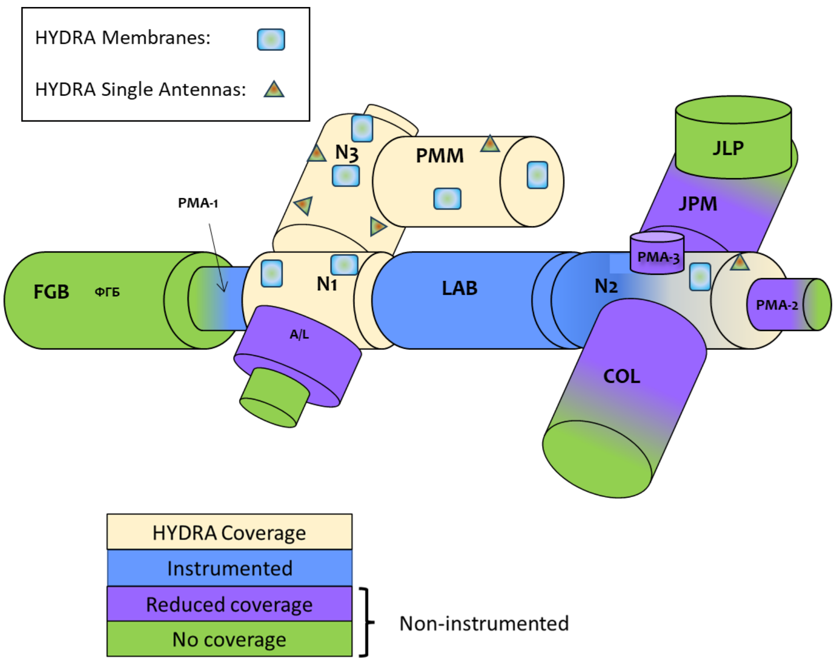


Figure 12. Notional layout of HYDRA technology for experiment on ISS.

IV. Trash Processing Technologies

A. The Trash Compaction Processing System (TCPS)

The TCPS is a waste management technology used to reduce trash volume by up to 70 percent, decrease potentially hazardous biological activity by heating the trash to 150 C, stabilize the processed trash for efficient storage, recover over 95 percent of the trash's stored water, and safen toxic gaseous given off during processing. The TCPS does not process metabolic waste, batteries, or sharp objects like razors.

The Next Step Space Technology Exploration for Partnership Broad Agency Agreement (BAA) Phase B, Appendix F contract[7] modification was awarded in 2022 to Sierra Space Corporation[8] to build a TCPS leading to an ISS technology demonstration. The tech demo is scheduled for early 2027, and it is hoped that at its conclusion the TCPS will continue to be used in support of ISS operations.

TCPS research activities at NASA Ames Research Center use an older model TCPS.[9] This system was built as part of an SBIR Phase II that was awarded in 2017[10] to Materials Modification Incorporated, which was subsequently bought out by Sierra Space Corporation. Current work includes testing "non-typical" trash[11] items that have a lower disposal frequency. These non-typical trash items are being tested to determine whether TCPS treatment will result in any toxin production, as it is likely that these items will be included in the astronaut waste stream, even unintentionally. Non-typical trash items are divided into two categories: (1) non-damaging to TCPS/non-toxin-producing, and (2) damaging/toxic. Examples in the first category include a leather belt, mechanical pencil, running shoes, and a small hand-held calculator with its battery removed. Some of the TCPS tested items are shown in Figure 13, with many more items planned for future tests. Items in the second category include inks or paints that could coat and poison the catalyst and adhesives, computer boards, or markers that could give off toxic compounds when heated.

Figure 13. Processing of non-typical trash items in the TCPS.

During a first round of testing to determine any issues, these items will be placed in a heated vacuum oven to see how they respond. This screening process will determine which waste items will likely be safe for further testing in the TCPS.

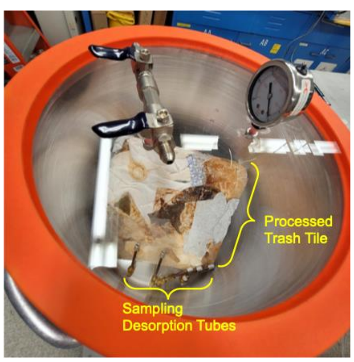


Figure 14. TCPS offgas capture using diffusion tubes in a sealed container.

Another area of concern is offgassing from processed trash. After processing, TCPS tiles will be temporarily stored in the spaceship cabin. For crew safety, the composition of the released gases needs to be determined. To perform these tests[12] a processed tile is placed in a sealed container along with diffusion tubes to capture the effluents, see Figure 14. At periodic intervals the diffusion tubes are removed and then processed using gas chromatography/mass spectrometry to determine the gas species present and the quantities.

Trash from the Crew Health And Performance Exploration Analog (CHAPEA) was also TCPS processed,[13] see Figure 15. The resulting tile density and composition of outlet gases were determined.

Figure 15. TCPS processing of CHAPEA trash.

B. Planetary Protection Policy Applied to Waste Management

On the Martian surface, waste will need to be stored in containers that prevent microbial release. Waste materials (leftover food, packaging material, sanitary wipes, fecal containers, etc.) are considered the greatest source of potential microbial contamination.[14] These microbes need to be contained for at least 50 years. Accidental release of terrestrial organisms will contaminate the local environment and confound planetary scientists in exploration of the Martian surface. Current work is to design filters that will be embedded on logistics containers that release interior gases while preventing microbial escape. These filters and their adhesives must be operational over a wide range of temperatures (-170˚C to +20˚C), must not be clogged by dust in the Lunar or Martian environment, and must filter any particulates above 0.2 micron in size. A test system under development is shown in Figure 16.

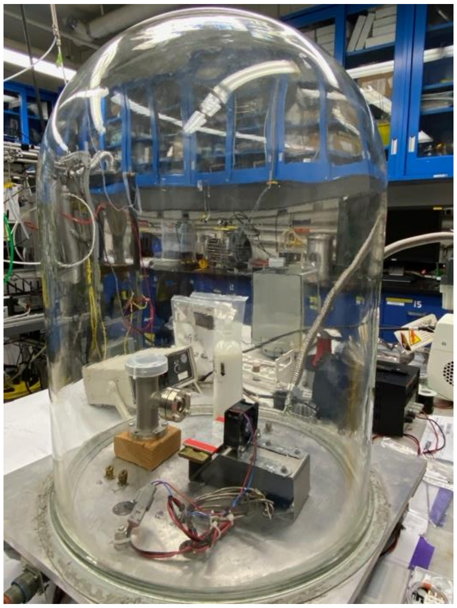


Figure 16. Test apparatus to study the use of filters for long-term waste storage on Mars.

C. Mechanical Trash Compactor

The mechanical trash compactor is a non-heated, pneumatic-driven, low mass and volume compactor for use while in transit or on a planetary surface. A laboratory benchtop testing system has been refurbished, see Figure 17. Initial testing shows an excellent ability to compact a crew of four's daily trash. Current work includes redesigning the bagging system and adding load and position sensors. This test system will measure compaction pressure, volume, surface forces, stability of processed trash, and spring-back. Insight from these studies will give an in-depth understanding of incorporating mission-dependent design requirements for future builds.

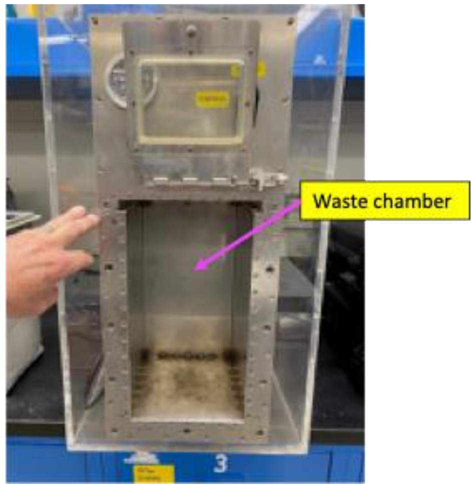


Figure 17. Mechanical compactor 11-liter waste chamber. The piston is fully retracted and the chamber door TCPS.

V. Systems Engineering and Integration (SE&I)

Through the LR portfolio's SE&I task, there is continued analyses supporting technology gap closure and LR infusion into Moon to Mars spacecraft and habitation. The LR portfolio maintains roadmaps for Metabolic Waste Management, Trash Management, Clothing and Cleaning, and Logistics Management. These technology roadmaps as well as key performance parameters, systems analyses and trade-off studies are periodically updated. The largest recent analytical effort is an integrated waste trade study, with results documented in a 2025 ICES paper[15].

When technology development tasks are not active in relevant areas, SE&I continues to shepherd minor activities such as NASA SBIR and Centennial Challenge involvement. This is the case for Advanced Clothing Systems, where progress continues to be made on fabrics for low-oxygen environments through one STTR and two SBIR contracts and a new SBIR subtopic in 2025[16]. Innovations in clothes cleaning for space are being developed through an SBIR contract[16] and a student[17] project. Additionally, LR subject matter experts are playing an integral role in the LunaRecycle crowd source challenge[17.]

There are ongoing analyses investigating fecal processing, trash-to-supply-gas[18] and matching recycling technologies to Artemis lunar missions[18]. A related study stemming from previous LR work is helping MCO's Food and Nutrition activity select the best refrigerator technology to achieve 5-year shelf-life for food on Mars missions.

VI. Conclusions

Logistics Reduction continues to work with numerous programs, providers and organizations preparing for Mars and Lunar missions. As these efforts become better defined, the work that LR is doing will inform decisions on hardware and operational strategies. Copious quantities of supplies or "logistics" consumables are required for current human space missions. Further details on their definition, quantities, and mass properties can be found in reference[19].

VII. Acknowledgments

This paper summarizes work that was performed by numerous NASA and contractor engineers, analysts, functional specialists, technicians, and crewmembers. While NASA programs MCO, ISS and Orion provide significant funding of the activities discussed, NASA recognizes the significant contributions of commercial partners, small businesses, and academic institutions.

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