53rd International Conference on Environmental Systems
20-25 July 2024, Louisville, KY, USA

ICES-2024-073

Logistics Reduction Advancements and Future Plans for NASA's 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], Justine Richardson[6]
NASA Ames Research Center, Mountain View, CA 94035

Ray Pitts[7], Anne Meier[8]
NASA Kennedy Space Center, FL, 32899

and

Curtis Hill[9]
Jacobs Engineering, Huntsville, AL 35806

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 project encompasses technologies for management of waste, trash, autonomous logistics, and clothing. This paper provides a status of work from 2023 in these areas including recent accomplishments and challenges encountered. Future objectives and plans for 2024 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) and Trash to Gas (TtG) is summarized with progress to date as well as information on how Jettison as an option is related. Progress and summary of recent accomplishment on the RFID (Radio Frequency ID) Enabled Autonomous Logistics Management (REALM) and InSpace Manufacturing technologies is detailed. Advanced Clothing System (ACS) and work in the area of Systems Engineering and Integration (SE&I) is also included. Status of the technologies, accomplishments and how the focus areas inform program decisions will be addressed.

---

[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 REAL, Avionics Systems Division/Mail Stop EV8.
[5] MCO Logistics Reduction TCPS Lead, Space Biosciences Division/Mail Stop SCB.
[6] MCO Logistics Reduction TCPS deputy Lead, Space Biosciences Division/Mail Stop SCB.
[7] MCO Logistics Reduction TtG Lead, Exploration Systems and Development Office/ Mail Stop UBE00
[8] MCO Logistice Reduction TtG Investigator, Exploration Systems and Development Office/ Mail Stop UBE00
[9] MCO Logistics Reduction InSpace Manufacturing OnDemand Manufacturing Principal Investigator, Jacobs Engineering, Hunsville, AL 35806

Nomenclature

ACS = Advanced Clothing System
AI = Artificial Intelligence
ALM = Autonomous Logistics Management
AM = Additive Manufacturing
AOWG = Advanced Organic Waste Gasifier
ARC = Ames Research Center
BAA = Broad Agency Agreement
CEP = Complex Event Processing
CTB = Cargo Transfer Bag
CO_2 = Carbon Dioxide
DLP = Digital Light Projector
EHD = Electrohydrodynamic
ESM = Equivalent System Mass
ExCap = Exploration Capabilities
FS = Full Scale
FTIR = Fourier-transform Infrared Spectroscopy
GCMS = Gas chromatography-mass spectrometry
HEPA = High Efficiency Particulate Air
HLS = Human Landing System
HMC = Heat Melt Compactor
IR = InfraRed
ISS = International Space Station
IMS = Inventory Management System
kNN = k-Nearest Neighbors
LEO = Low Earth Orbit
LOO = Lavatory On-Orbit
LR = Logistics Reduction
M2M = Moon to Mars
m^3 = cubic meter
MCTB = Multi-purpose Cargo Transfer Bag
MPCV = Multi-Purpose Crew Vehicle
MCO = Mars Campaign Office
NextSTEP = Next Space Technologies for Exploration Partnership
ODME = On-Demand Manufacturing of Electronics
NASA = National Aeronautics and Space Administration
OSCAR = Orbital Syngas/Commodity Augmentation Reactor
P&G = Procter and Gamble
PMM = Permanent Multipurpose Module
QR = Quick Response Code
REALM = Radio Frequency Identification Enabled Autonomous Logistics Management
RFID = Radio Frequency Identification
RSSI = Received Signal Strength Indicator
SBIR = Small Business Innovation Research
SCCS = Source Contaminant Control System
SE&I = Systems Engineering and Integration
STMD = Space Technology Mission Directorate
STTR = Small Business Technology Transfer
TCPS = Trash Compaction Processing System
TGA = Thermogravimetric Analysis
TIH = Toilet Integration Hardware

TD = Technology Demonstration
TtG = Trash to Gas
TRL = Technology Readiness Level
UPA = Urine Processor Assembly
UWMS = Universal Waste Management System
VOC = Volatile Organic Compound
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) Project. In addition to reducing mass, volume, and crew time, it is important that developments directly address exploration technology gaps[1] focused on enabling exploration missions to Mars 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. Surface technologies can be demonstrated on the ground are equally important for logistics reduction.

The MCO LR project scope includes technology areas that primarily target crew consumables, logistics management, and waste management. This paper provides an overview of the technologies development progress over the past year and provides references to papers that provide additional details. Direct mass reduction of logistics is being investigated with longer wear crew clothing, compact toilets, optimization of fecal waste containers mass and volume, and on-demand manufacturing in lieu of dedicated logistical spares. Repurposing of items also reduces departure mass and can be achieved with laundering of crew clothing and reconfiguring cargo transfer bags from launch vehicles to 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. Trash can also 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 focus 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-2 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.[2] The Orion UWMS was delivered to KSC 12/23/2019 and was installed into the Artemis-2 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 2).

The UWMS collects waste 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 common 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 ICES-2024-070.[5]

Treatment of the urine to preclude solid deposition, biological and fungal growth and as well as odor is provided for both units. Because the Orion mission is a short duration flight, a solid form of Oxone is used to treat the urine which is vented from the vehicle after a short storage period. On ISS, urine is recycled after collection in the UWMS. Urine treatment is from a very strong phosphochromic acid which is dispensed into the urine stream by a Dosing Assembly. The ISS UWMS unit is more complex than the Orion unit because of the addition of an active dosing assembly for delivery of accurate quantities of urine pretreat into the urine stream before it travels downstream to the Urine Processor Assembly (UPA) on ISS. The UWMS uses a dose pump to deliver defined volumes of water and pretreat concentrate, mix them, and then measure the conductivity before it is injected into the urine as it comes into the UWMS from the urine funnel and urine hose. Figure 1 shows the UWMS Dosing Assembly with the Dose Pump identified. Also shown is the pretreat quality indication device, a conductivity sensor. This sensor is being redesigned and is expected to be delivered in 2024 for use with the redesigned dose pump check valve.

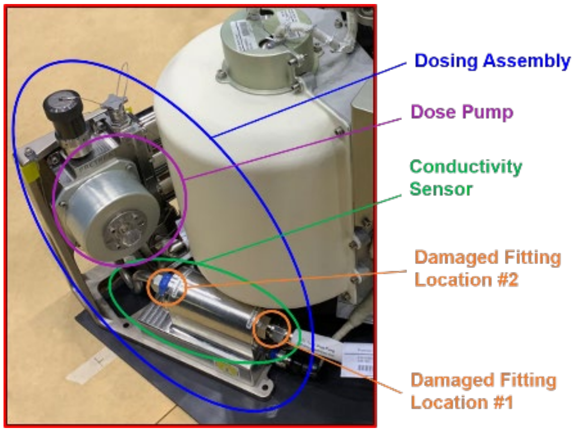


Figure 1. ISS UWMS Dosing Assembly with Dose Pump and Conductivity Sensor identified.

Completion of a technology demonstration on ISS is currently pending resolution of technical issues with the hardware. A shorter Artemis-2 demonstration on ISS was attempted in February 2023. More information on the technical issues can be found in referenced papers. [3,4,5, 6] A technical issue was discovered with the dose pump. The pretreat concentrate was not dispensing properly. This was confirmed on-orbit by data analysis in near real-time, visual confirmation of the color of the dosed fluid (clear with no tell-tale orange color), and subsequent data analysis with operational changes. This data pointed to a failed pretreat inlet check valve in the dose pump. The unit was returned to the ground for evaluation which confirnmed catastrophic failure of the check valve. Internal components were found in pieces and the check valve could not perform it's intended function. Brittle failure was indicated by evaluation and analysis. The material used was PEEK 450 which is not indicated for use with a strong acid. Redesign of the check valves with metallic components which are compatible with pretreat concentrate is ongoing and a resumption of the Artemis-2 demonstration is planned.

Figure 2. UWMS, ISS unit in Node 3 of ISS (left) and Orion unit installed in Artemis-2 (right)

Based on crew feedback from the aborted Artemis-2 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[6]. The seat allows the fecal bag to be installed over the seat so it can contact the body during use. 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 is planned for 2024. If positive results are received from redesign and on-orbit crew evaluation it will allow the Artemis-2 UWMS to be upgraded before launch. Evaluation on ISS is needed to confirm air flow and crew accessibility.

For exploration outposts to become sustainable, technologies for fecal processing that recover water and stabilize human waste will become more important. These are already being investigated through Small Business Innovation Research (SBIR) contracts[7,8,9,10]. Advanced Fuel Research investigated torrefaction of the feces at temperatures up to 250°C in several SBIR contracts. Another effort with Ultrasonic Technology Solutions has a phase II-E SBIR contract focusing on using piezoelectric transducers to mechanically shake the water out of the feces with ultrasonic waves. They have completed a ground prototype and some zero-g testing[1,30]. These and other fecal processing technologies were compared in an analytical study described in section VII.

III. Autonomous Logistics Management Tracking Technologies

Experiences with logistics management on the ISS have identified a critical need for automation in logistics management tracking technologies. Over 92,000 items are actively tracked on the ISS Inventory Management System (IMS) database. Historically, about 13,500 items have been reported lost of 405,000 tracked items in the ISS program life. Since 2017, at any time about 3,000 items in the active item population would have RFID tags in addition to the barcode marking on all tracked items. However, recently updated ISS requirements will result in a much larger percentage of items tracked with RFID. While more remote habitats may not initially experience the volume of cargo that is now typical on the ISS, the cost and impacts of replenishing lost items or not having items when required is likely to be much greater. Items tracked in the database are considered “reportable items”, which are items for which the value of tracking exceeds the cost. Technologies deployed to track the reportable items can also vary depending on the criticality of the item. As tracking technologies mature, enabling tracking of more types of items within an acceptable cost range, the number of reportable items is expected to increase. NASA embarked on the RFID(Radio Frequency Identification)-Enabled Autonomous Logistics Management (REALM) project to evaluate these technologies on ISS, as well as to understand how to implement them on a remote outpost and how to tailor the solution to meet different mission constraints. The following sub-sections detail the experiences with these technologies as well as forward work.

A. Overview

The REALM experiments were divided into three foundational phases, REALM-1, -2, and -3. REALM-1 comprises a constellation of fixed readers and antennas in the open region of instrumented ISS modules. REALM-2 is based on a robotic free-flyer equipped with an RFID reader and antennas, and REALM-3 is based on a fixed reader similar to REALM-1, but with the signals routed directly into dense stowage regions. All data is downlinked to a Complex Event Processing (CEP) center where the data is reduced to key inferences, chief of which is item location, by machine learning engines. Detailed descriptions of REALM-1,-2, and -3 were reported in a previous publication[2]. Here, we discuss additions to the REALM experiments with the objectives of closing performance gaps in total visibility of asset tags and the accuracy of location estimates. This addition is referred to as the Drawer Monitor System (DMS) and is based on sensors added to RFID tags for additional functionality.

B. Drawer Monitor System

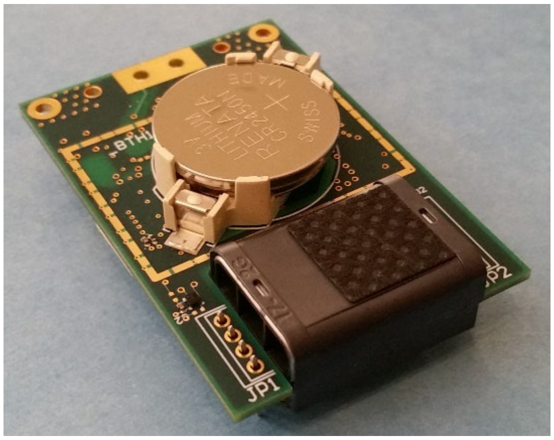


Figure 3. Environmental RFID Sensor (CO2).

The REALM-3 Drawer Monitor System (DMS) is an RFID sensor system targeted to logistics purposes. In addition to the typical capability of an RFID tag to respond with its unique identification code, RFID sensors have onboard data acquisition and sensor capabilities. The sensed data can then be transmitted over the RFID channel to the reader. For RFID standards based on passive back-scattering, such as EPC Gen2, the communication from the tag requires no battery. Thus, for sensing applications that can be satisfied with low data rates and low power sensors, a paradigm of RFID sensing can be achieved with very long lifetime on small coin cell batteries, and, in some cases, with harvested RF energy. Figure 3 shows an example of an RFID tag with an embededded CO2 sensor, and Figure 4 shows the sensor tag battery life for two different coin cell battery types, CR2032 and CR2450, as a function of the sample rate, in order to convey the potential sensor lifetime with this general low-power sensing architecture CO2 sensing was of early interest in evaluation of this technology, so early battery life studies were conducted with this specific low-power sensor. The battery selected for the DMS tag is the CR1632, as it was already certified for applications on ISS. These are provided to show the potential use of this technology. Other sensing modalities amenable to this architecture include pressure, temperature, humidity, and strain, as well as others.

One of the primary objectives of the DMS experiment is to demonstrate and evaluate this ultra-low power RFID sensing paradigm for a broad range of space applications. That is, although the DMS tag incorporates an accelerometer-based motion sensor for logistics tracking context, the RFID sensing architecture is broadly applicable to a much wider set of applications, such as CO2 sensing. In this broad paradigm, the sensor data is transferred through the RFID communication channel along with logistics data.A second primary objective of the DMS experiment is to evaluate an RFID sensor system that adds additional context to improve the localization of asset tags, which utilize standard EPC Gen2 passive RFID tags. The concept of operations for the DMS presumes the presence of a fixed reader system with open-air antennas as in REALM-1. The readers typically capture the presence of tags in open space with high probability. However, RFID "visibility" is frequently lost when the tags are placed within a metallic enclosure or behind other RF-opaque materials or objects. At this point, the tagged asset is usually not seen again by the open-air antennas until the tag has been uncovered. By adding DMS motion sensing tags to stowage doors, door open/close events can be time stamped and utilized by machine learning to improve inferences on where an item was placed. The REALM-1 open-air antennas would provide an indication that an item is in the vicinity of the stowage location, and event data from the tag on the opened door would provide context leading to a likely association between the identified door and the tagged article.

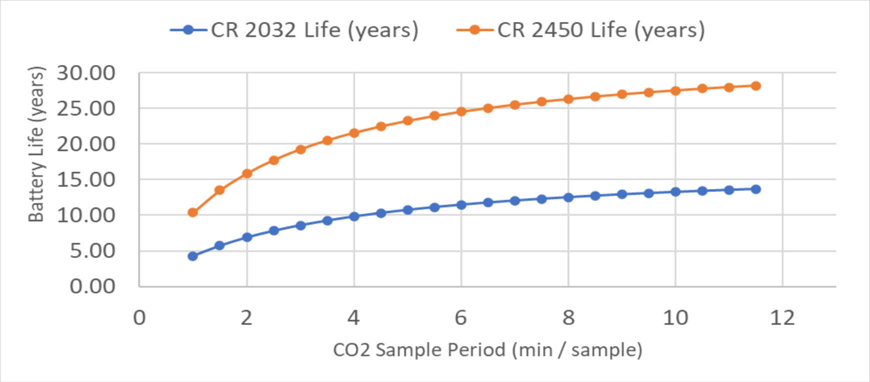


Figure 4. RFID CO2 sensor battery life based on sample rate.

The DMS tag comprises a custom meandered line ½-wave dipole antenna, an Impinj Monza RFID chip, an MSP430 microcontroller, and a 3-axis accelerometer. The single-board assembly is mounted in a printed Ultem housing (Figure 5). The sensor tag is programmed to record time stamps for events that register above a minimum threshold. Threshold settings that are either too low or too high result in missed events or false alarms that can unnecessarily drain the battery. A time stamped event results in the time stamp being added to an on-board queue as well as a modification in one of the bits of the tag EPC identification code. That change in EPC code serves as a notification to the reader that the tag has event data ready to be retrieved. The process is designed to not significantly detract from the task of the readers to conduct constant queries of asset tags within read range. Figure 6 shows the estimated average current consumption of a DMS tag and the expected battery lifetime based on the number of events per hour.

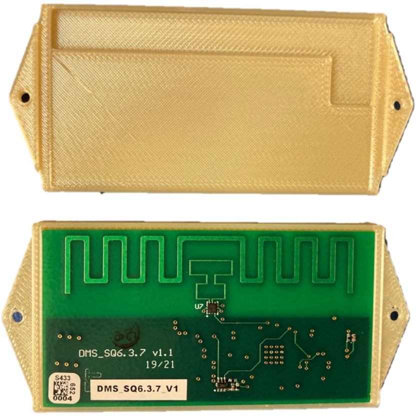
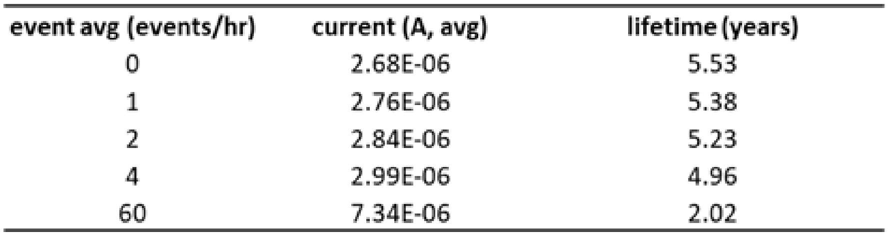


Figure 5. DMS RFID Motion Sensor tag. (~2.75" x 1.75" x 0.3")



event avg (events/hr)	current (A, avg)	lifetime (years)
0	2.68E-06	5.53
1	2.76E-06	5.38
2	2.84E-06	5.23
4	2.99E-06	4.96
60	7.34E-06	2.02

Figure 6. DMS tag expected lifetime and average current based on number of events per hour.

C. DMS Installation on the International Space Station

The DMS tags were launched on NG-18 in 2022 and installed in December. A total of 16 tags were installed using Velcro patches, 4 on the 4 doors of the NOD1S4 zero-gravity stowage rack (ZSR), and 12 on the doors of the NOD1O4 ZSR. Both ZSRs are accessed frequently as they are predominantly used to store food bulk overwrap bags, or “BOBs. The NOD1S4 rack is the site for the integrate REALM-3 Smart Stow, which serves as a good truth source for evaluation of the DMS system. Figure 7 shows the symbolic layout as well as the locations of NOD1S4 and NOD1O4 in ISS. Figure 8 shows Four DMS tags on NOD1S4 ZSR doors in Space Vehicle Mockup Facility at JSC and Figure 9 shows Six DMS tags (of 12) on NOD1O4 ZSR doors on ISS.

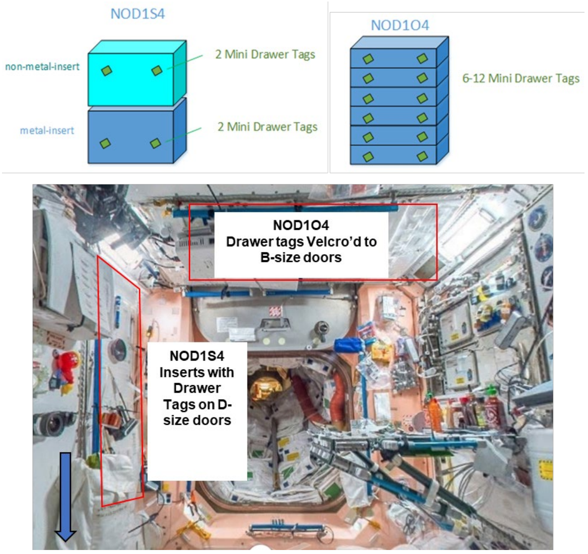


Figure 7. Symbolic placement of DMS tags on NOD1 ZSR doors, and locations of the ZSR racks in ISS NOD1.

Figure 8. Four DMS tags on NOD1S4 ZSR doors in Space Vehicle Mockup Facility at JSC.

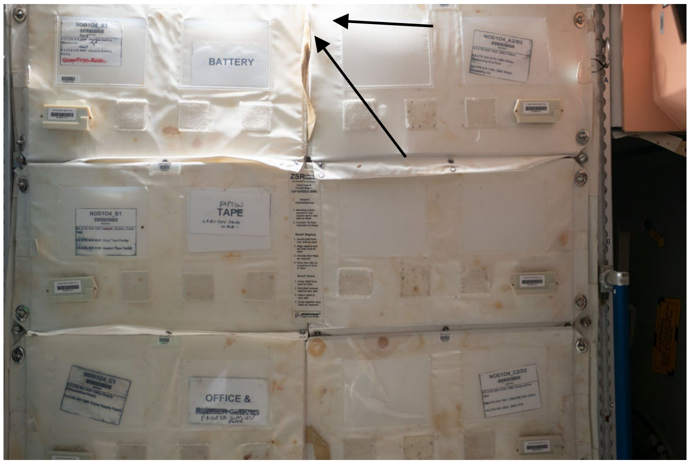


Figure 9. Six DMS tags (of 12) on NOD1O4 ZSR doors on ISS.

D. Initial DMS Performance on the International Space Station

The DMS tags were commissioned and evaluated beginning in January 2023. Only a few tags of the 16 tags responded, and it became clear that most of the tag batteries had become depleted. Subsequent ground test and analysis of the returned tags revealed that a firmware bug on the tags prevented them from going into a deep, ultra-low current sleep state from the time of hardware handover for launch until the time of commissioning. Thus, the low charge on a handful of responding tags permitted only a limited evaluation. However, that evaluation of the subset of tags over a period of about 30 days was largely positive. The integration of the sensor system did not adversely impact the regular queries of asset tag data, and data communication between the reader and DMS tags worked as expected. Registered motion events largely coincided either with mealtimes, when activity is expected at the targeted racks, or with planned stowage events at those racks. Given the challenge in estimating the optimal accelerometer threshold settings (drawer opening events) for the 0-g environment, the system allows for remote programming of these DMS tag settings. However, based on the limited observations and the coincidence with likely events, the settings were not modified.

E. Forward plans for the DMS System

After correcting for the bug responsible for the early power depletion and implementing additional improvements to further lower current drain during different stages of the tag's operation, the tags underwent extensive testing in both dormant and active states for a period exceeding 4 months. Additional test processes were also established to verify that the tags are successfully placed into a low-power sleep mode. New flight batteries were installed prior to sealing the original tags prior to handover for launch. Eighteen of the DMS tags were launched on SpX-30 in March 2024.

IV. Additive Manufacturing and Logistics Reduction

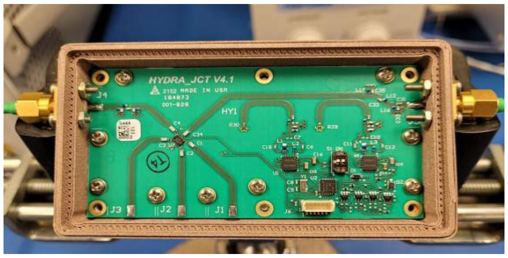


Figure 10. HYDRA PCB in ISM 3D-printed housing. Weight: 56% of Aluminum housing, RF loss: 2.25 dB, 1.8 dB for AL.

The LR project has been working on incorporating new additive manufacturing (AM) technologies as additional opportunities to reduce launch mass and/or improve performance of the REALM system. In-Space Manufacturing (ISM) activites have been evolving over the past several years[37] but are a recent addition to the MCO LR project. There are synergies with manufacturing of REALM antennas and housing (the REALM-2 flight housing is additive manufactured (see Figure 10)). There are SBIR technology developments by Cornerstone[38] for replacing packaging foam with printed lightweight structures that can be processed into manufacturing feedstock. New ISM capabilities in additive electronics have been incorporated for printed wireless sensors on RFID tags and for the additive fabrication of conductive housings for performance and shielding. These new AM techniques allow for significant weight savings without a sacrifice in system performance.

In addition, LR has worked with ISM to design and fabricate new titanium RFID antenna bases to replace bulky polymer/metal composite bases used in the past. These new titanium bases are much lighter and stiffer as antenna bases, leading to significant weight reductions and the potential expansion of the REALM system with additional nodes for performance enhancement.

These new AM parts were designed from the start with additive manufacturability considerations, so they take full advantage of this new processing capability for reduced weight and volume (Figure 11). Redesigns and updates will be much easier in the future with on-demand printing. NASA will have this capability on ISS in 2024, so these parts and new designs can be on-demand additively printed in space for immediate implementation and replacement.

Newly developed ISM/ On-Demand Manufacturing of Electronics (ODME) developed additive manufacturing systems will enable a new range of 3D-printed devices such as the fully printed CO2 sensor in Figure 11, but will also enable advanced manufacturing of a wide range of printed sensors and microelectronics. New Electrohydrodynamic (EHD) Inkjet deposition systems are enabling the printing of advanced semiconductor devices in microgravity, including latest-generation memory chips. CO2 sensors can be used for various ECLSS applications wherever readings of CO2 (or similar sensors) are used. The REALM networks allows collection of data over the existing framework and the ISM printed sensor reduce mass and volume for these applications.

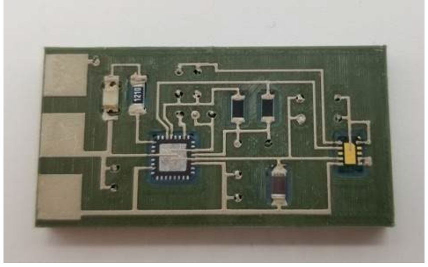


Figure 11. AM Carbon Dioxide (CO_2) sensor.

V. Trash Processing Technologies

Trash processing reduces the trash stowage volume to gain back valuable storage and habitable space. Biological control and safening of the trash is needed for crew health and safety. Recovering water from the trash is highly desirable. The residual dry trash also has properties that can be utilized to convert to useful gases for fuel or commodity use as well as residual solids that will contain carbonaceous ash with crop nutrients and metals. The processed residual trash must be in a stable physical form and biologically inert for long-term storage.

A trash management strategy is needed for exploration missions and is useful for current strategies in dealing with trash on ISS. Logistics Reduction is working various technologies to deal with trash on exploration vehicles, habitats, and missions. The selected technology(ies) will be optimized for each application and will include a combination of the options currently being developed. The strategies include compaction of trash both with and without a heat element, and reduction of trash to a gas element. Studies are underway to evaluate how each of these can be used either alone or in combination. Additional data would be gained from trash compaction and trash to gas technologies demonstration on ISS along with ground testing of hardware.

A. The Trash Compaction Processing System (TCPS)

The TCPS is a non-metabolic, waste management technology used for reducing trash volume, eliminating hazardous biological activity, stabilizing processed trash for efficient storage, recovering water, and safening toxic gaseous effluents during processing. A NextSTEP Broad Agency Agreement (BAA) Phase B contract modification was awarded in 2022 to Sierra Space Corporation to build a TCPS for an ISS flight demonstration with the possibility for continued use to support ISS operations.

Risk reduction activities at NASA Ames Research Center use an older model TCPS to run experiments. This work includes measuring particulates produced from handling processed trash tiles, as well as comparing bagged and unbagged trash processing for water recovered, particulates produced, final trash density, and gaseous effluents produced. Items in the trash are from non-metabolic astronaut waste and include uneaten food remains, hygiene items, packaging materials, and used clothing. Upcoming testing will expand the trash inventory to include other items with a lower disposal frequency such as epoxy putty, HEPA filters, pens, markers, calculators, etc. It will be necessary to know if any toxins are produced from TCPS processing of these items since it is likely they will be included, even unintentionally, in the trash. Another area of concern is off-gassing from processed trash. For crew safety, the composition of effluent gases needs to be measured. A test program is being developed to address this issue.

Figure 12. Processing of Bagged Trash in the TCPS.

B. Planetary Protection Policy Applied to Waste Management

This task is part of a technology development for long-term (> 50 years) waste storage on the Martian surface to prevent microbial release and uphold planetary protection requirements. Accidental release of terrestrial organisms on the Martian surface will contaminate the local environment which can confound planetary science and permanently alter the Martian ecology. Current emphasis is to develop ways to apply unheated filters on logistics containers that will be re-used for waste disposal once unpacked. These filters and their adhesives must be operational with a wide range of surface temperatures (-170C to +20C), must avoid clogging from dust in the lunar or martian environment, and are required to filter any particulates above 0.2 um in size. A proposed test apparatus for filter clogging is given in Figure 13 below.

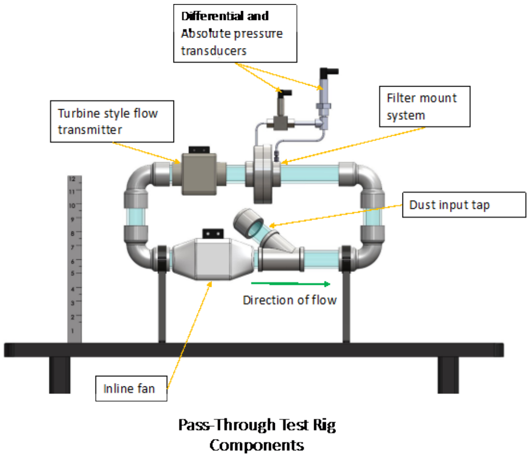


Figure 13. Proposed Test Apparatus To Study the Use of Filters For Long Term Waste Storage on Mars.

C. Waste to Base

The purpose of this task is to develop low Technology Readiness Level (TRL) concepts into workable solutions to recycle, reuse, and repurpose trash. A recent (June 2022) crowdsource challenge under the STMD's NASA Tournament Lab was completed with 22 prizes awarded. A novel concept that is being studied is the use of water-absorbent polymers as a packing foam replacement. It is an engineering challenge to see if impact and vibration requirements can be met while avoiding any tears or ripping of material containers. Since the water can be removed from the polymers, there is no weight penalty due to the additional density during liftoff. Another concept being investigated is the use of bio-degradable products whenever possible for composting rather than throwing materials away.

D. Manual Trash Compactor

This task is to design a manual, low mass, low volume, and easy to use manual trash compactor for use while in transit or on a planetary surface. Compaction pressures are not expected to be high enough to recover water, and no heating will be used to safen the trash. Recently a laboratory benchtop testing system has been refurbished. This test system will allow for measurements of compaction pressure, final trash volume, stability of processed trash, particulates produced, and gas effluent composition. Insight from these studies will give a much better understanding of design requirements of the desired mechanically hand-operated system.

Figure 14. Laboratory Benchtop Trash Compaction Test System.

E. Trash-to-Gas and Trash-to-Supply-Gas Processing

The Trash-to-Gas (TtG) and Trash-to-Supply-Gas (TtSG) waste management approach utilizes a thermochemical process to degrade waste items into useful products such as synthetic gas (syngas), water, and recoverable solids. Thus, this technology can be useful for both waste mass and volume reduction and resource recovery in the form of ECLSS commodities (water, oxygen) or propellant (oxygen, hydrogen, methane, etc.). The term TtG is used when the primary focus of the product stream from the thermochemical process is tailored to maximize gas production as to most efficiently remove waste mass from the spacecraft via gas venting. The term TtSG is used when the primary focus of the product stream is to maximize recovery of water along with other useful gases and solids from the waste.

Figure 15. Subscale Trash to Gas OSCAR reactor.

In 2023, the TtG technology development team at NASA Kennedy Space Center began work on a full-scale Engineering Development Unit (EDU), sized for a crew of four. In the pursuit of scaling up this technology from the relatively small throughput of the Orbital Syngas/Commodity Augmentation Reactor (OSCAR) system that was demonstrated during a suborbital flight campaign, the EDU was aptly named Orbital Syngas/Commodity Augmentation Reactor – Full Scale (OSCAR-FS). OSCAR-FS is a ground unit designed to perform a long-duration demonstration (>30 days) of the TtG process to elevate the technology readiness level (TRL) of this technology to TRL 5. This key demonstration will also highlight lessons learned such as full-scale mass, power, & volume estimates, cycle time, and expected failure modes. As of October 2023, the OSCAR-FS system has completed the conceptual design and analysis of a high throughput reactor. This reactor is designed for combustion processing of waste (similar to OSCAR) but is capable of being reconfigured to enable other thermochemical processes such as pyrolysis. The reactor design is sized for the input of a single 8L trash containment vessel, as shown in a conceptual TtG design in Figure 16.

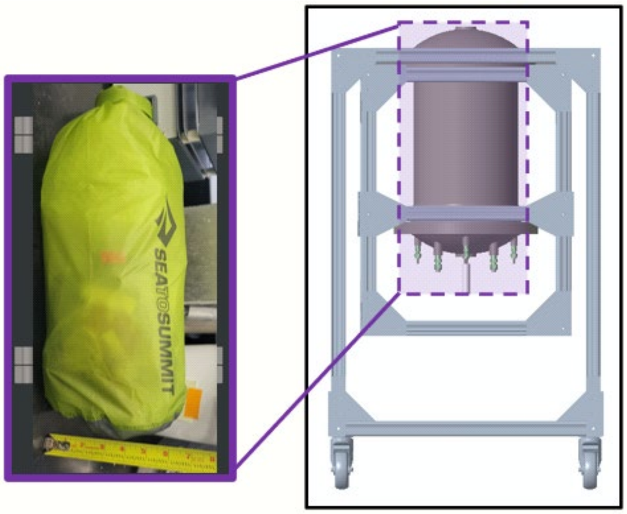


Figure 16. TtG Reactor Conceptual Design

Cecilia Energy has completed a Phase I SBIR project, successfully converting waste plastics (polypropylene, polyethylene, nylon) into hydrogen gas and carbon utilizing microwave-assisted thermocatalytic decomposition of the crew waste. Cecilia Energy has since been awarded a Phase II SBIR to continue the scale-up development of this TtSG technology.

One potential application of TtG solid products has been explored via a Center Innovation Fund (CIF) project in collaboration with NASA MSFC In-Space Manufacturing (ISM) team. In this study, aluminum waste from astronaut food packaging was successfully extracted via TtG processing and converted into aluminum additive manufacturing feedstock. The results from this study are detailed in a separate ICES 2024 publication.

Another application of the technology byproducts was demonstrated via a CIF that collected and analyzed the solids remaining from commercial table-top composting units and TtG technology processing units. Elemental composition of the remaining solids, and potential water-soluble nutrients were measured and then mixed with lunar and Martian regolith to observe germination of Daikon Radish microgreens. Germination was successful in some of the regolith and regolith mixtures, while other factors may have inhibited the growth of crop production in the soil mixtures. While additional grow-outs are necessary to determine the full extent at which the waste solids and regolith soils can be used for crop production, the preliminary results were promising and facilitate the plausibility of continuing the research to merge technologies that can close the space waste cycle and enable regenerative life support from all materials sent off-world.

VI. Advanced Clothing Technologies

Clothing represents about one-fourth of an astronaut's crew provisions (not including food) and there are no current clothes washer and dryers certified for space. Thus, LR's Advanced Clothing Systems (ACS) task has been exploring longer-wear and lighter-weight clothing as well as low-resource methods of cleaning clothing for Moon to Mars (M2M) missions. To improve the trade off for laundry in space, the LR project has been working with NASA's Life Support Systems project, starting by defining the composition and expected quantity of laundry wastewater including an optimized detergent. Through a Space Act Agreement with Procter and Gamble (P&G), researchers developed Tide Infinity*TM* detergent to meet the constraints of being fully degradable and compatible with closed loop air and water systems[26]. Evaluation of this detergent has continued over the past year in commercial washer/dryer combination machines in several NASA tests including a bioreactor water processor at Texas Tech University[27] and the Crew Health And Performance Exploration Analog (CHAPEA) at JSC[28]. Another innovative laundry solution is being pursued through a Phase 2 SBIR contract with Ultrasonic Technology Solutions, which could create a small device that used ultrasonic vibrations to both wash and dry clothing (ref. UTS 2024 paper).

Another technology being developed by the LR team in collaboration with the Life Support Systems project's air team and small business partner Faraday Technologies is an in-situ Hydrogen Peroxide Generator (HPG). This technology can reduce launch mass by allowing housekeeping disinfectant wipes to be wetted on-orbit using hydrogen peroxide produced from recycled water.[29] ground testing and hardware lifetime improvements are currently underway at JSC.

Another important technology gap the ACS team continues to close is compatibility of clothing with high oxygen atmospheres that will likely be found in exploration habitats where frequent spacewalks are planned. Clothing for ISS is certified to meet flammability requirements up to 30% O_2 at 10.2psia, but capability up to 36% O_2 at 8.3 psia is desired for lunar and planetary habitats. Several SBIR and STTR contracts are underway looking into fire retardant treatments as well as fundamentally lower flammability fibers. A phase 2 STTR contract was recently awarded to Paragon and North Carolina State University to investigate novel fiber blends for high oxygen environments. Two phase 2 SBIR contracts were also awarded to InnoSense, LLC for "Nanolayer-Coated Flame-Retardant Fabrics for Space Crew Clothing" and to Materials Modification, Inc. for "Flame Retardant Polyamide Fibers for Space Crew Clothing".

VII. Systems Engineering and Integration (SE&I)

The LR project takes a system's engineering approach to ensure that developed technologies help close technology gaps, benefit exploration missions, and integrate well with other systems in habitats and spacecraft. Technology roadmaps, key performance parameters, systems analyses and trade-off studies are continually updated. The LR project maintains roadmaps for Metabolic Waste Management, Trash Management, Clothing and Cleaning, and Logistics Management.

Previous studies showed that some missions, such as high energy vehicles like a Mar's Transit Hab, have a very strong driver to get rid of waste during the mission to reduce vehicle mass and thus propellant use, while others may benefit more from recycling waste products.[30,32] A broad integrated waste study is underway in which waste management strategies are linked to mission level integration questions such as degree of water closure, EVA frequency and mission requirements. Water is usually the first driving factor in determining when processing and resource recovery from waste streams pays off, but the longer missions become, the more important it becomes to create a circular ecosystem that reuses all wastes. Details and progress of the integrated waste study can be found in reference 32.

Another specific trade study conducted in 2023 was a comparison of urine brine processing to trash processing for water recovery. In this unpublished study, the difference in equivalent system mass (ESM) was calculated when a Brine Processor Assembly (BPA)[33] or Trash Compaction and Processing System (TCPS)[34] was added to the life support systems of several different habitats for missions of different durations. A four-person crew was considered in each case, including all resources and consumbles needed to run the systems, and best available performance data was used for the calculations. BPA has undergone flight demonstration on ISS in recent years and TCPS is scheduled for a flight demonstration on ISS in 2026.

Equivalent system mass is an analytical technique often used to compare technologies or systems based on their overall launch mass difference from a baseline. Equivalency factors[35] are used to convert required volume, power, and cooling resources to launch mass, in addition to the added mass of the technology hardware itself. In this case, BPA and TCPS produce savings, or a net decrease in launch mass by recovering water from wastes so that less water needs to be launched. Table 1 shows the net ESM benefits for each technology for 1-year on ISS and even greater benefits for the Mars Transit Habitat. This does assume that the recovered water helps close the water balance and not create a suplus of recycled water, which could actually be counterproductive for the mission. For a single 30-day Lunar Habitat mission, the water recovery is not enough in either case to outweight the technology hardware, thus savings are negative. However, if the device can be used in a subsequent Lunar Habitat mission, the savings will soon be positive. Note that both technologies have a launch mass reduction benefit for missions longer than a month or two and could be used together whenever more recycled water is needed. Beyond water recovery, both technologies have other benefits associated with reducing volume and other nuisance aspects of the waste products.

Table 1. BPA and TCPS Comparison of Benefits

		ESM Equivalency Factors			**Technology**	
		Volume	Power	Cooling	ESM Savings with	
Mission	**# Days**	*(kg/m^3)*	*(kg/kW_e)*	*(kg/kW_{th})*	**BPA**	**TCPS**
ISS	365	67	133	349	416	61
Mars Transit	850	18	69	88	1176	786
Lunar Hab	30	18	78	98	-60	-197

VIII. Conclusion

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.

IX. Acknowledgments

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 36. The Logistics Reduction project continues to work with numerous programs, providers and organizations preparing for Mars and Lunar missions to reduce the logistical burden. As these missions become better defined, the work that LR is doing will inform decisions on hardware and operational strategies.

X. References

[1]McKinley, M. K., Ewert, M. K., Borrego, M. A., Orndoff, E., Fink, Patrick., Sepka, S., Richardson, Justine., Meier, Anne., Hill, Curtis., “Advancements in Logistics Reduction for Exploration Missions,” *52nd International Conference on Environmental Systems,* ICES-2023-040, July 16-20, 2023, Calgary, Canada

[1]Schneider, W. F., Perry, J. L., Broyan, J. L., Macatangay, A. V., McKinley M. K., Meyer, C. E., Shaw, L. A., Owens, A. C., Toomarian, N., Gatens, R. L., “published) paper submit# ICES-2020-200, July 2020.NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2019 to 2020 Overview,” 50th *International Conference on Environmental Systems*, Lisbon, Portugal,

[2]McKinley, M.K, Broyan, J.L, Shaw, L, Borrego, M., Carter, D., Fuller, J., “NASA Universal Waste Management System and Toilet Integration Hardware Delivery and Planned Operation on ISS. *50th International Conference on Environmental Systems,* ICES-2021-403, July 7-11, 2021, virtual.

[3]Borrego, M. A., Zaruba, Y. G., Broyan, J. L., McKinley, M. K., Baccus, S., “Exploration Toilet Integration Challenges on the International Space Station,” *49th International Conference on Environmental Systems,* ICES-2019-154, July 7-11, 2019, Boston, MA, USA.

[4]McKinley, M.K, Borrego, M., Broyan, J.L., “NASA Universal Waste Management System and Toilet Integration Hardware Operation on ISS – Issues, Modifications and Accomplishments, *51st International Conference on Environmental Systems,* ICES-2022-73, July 7-11, 2022, St. Paul, MN, USA.

[5]McKinley, Melissa, Borrego, Melissa, DeRees, Williamson, Jill, Kaufman, Cory, “NASA Exploration Toilet On-orbit Results and Impact on Future Missions”, *52nd International Conference on Environmental Systems,* ICES-2023-038, July 12-16, 2023, Calgary, Canada.

[6]Borrego, Melissa, DeRees, Walker, Mary, Carmona, Yvette, Eifert, Alexandra, Marshall, Alisa, “Evolution of the Next Exploration Toilet through Human-in-the-Loop (HITL) Testing, *52nd International Conference on Environmental Systems,* ICES-2023-038, July 12-16, 2023, Calgary, Canada.

[7]https://sbir.nasa.gov/SBIR/abstracts/19/sbir/phase1/SBIR-19-1-H3.02-3285.html, UMPQUA Research Company. Graded Temperature Fecal Dryer-Densifier.

[8]Boyce, S.P., et al., “Water Recovery from Human Metabolic Waste: System Design, Analysis, and Preliminary Results”, ICES-2021-460, *50th International Conference on Environmental Systems*, July 7-11, 2021, virtual.

[9]Bigelow, J., et al., “Optimization of Ultrasonic Drying Rate and Efficiency for Spacecraft Solid Waste Management”, ICES-2022-218, *51st International Conference on Environmental Systems*, July 7-11, 2022, St. Paul, MN .

[10]Serio, M., Wojtowicz, M., Cosgrove, J., Stapleton, T., Lee J., “Operational Data for a Full Scale Prototype Torrefaction Processing Unit (TPU) for Spacecraft”, ICES-2019-291, July 7-11, 2019, Boston, MA, USA.

[11]Klopotic, J.M. and Wetzel, J.P., “Trash Compaction and Processing System Development and Testing”, 51st International Conference on Environmental Systems, ICES-2022-104, 10-14 July 2022, St. Paul, Minnesota.

[12]Sepka, S., Chen, T. T., Ewert, M., Venigalla, C., and Lee, J., "Design of a Jettison System For Space Transit Vehicles," 51st International Conference on Environmental Systems, ICES-2022-129, 10-14 July 2022, St. Paul, Minnesota

[13]Sepka, S., Shapiro, A., Ewert, M., Richardson, J., "Considerations For Waste-to-Base Future Research Paths," 52nd International Conference on Environmental Systems, ICES-2023-75, 16-20 July 2023, Calgary, Canada

[14]Olson, J. A., Chai, P., Rinderknecht, D., and Meier, A. J. A Comparison of Propellant Requirements for Crewed Mars Missions Incorporating Different Waste Processing Technologies. Presented at the ASCEND, Las Vegas, Nevada & Virtual, 2021.

[15]Olson, J., Rinderknecht, D., Essumang, D., Kruger, M., Golman, C., Norvell, A., and Meier, A. “A Comparison of Potential Trash-to-Gas Waste Processing Systems for Long-Term Crewed Spaceflight.” 50th International Conference on Environmental Systems, ICES-2023-282, 11-15 July 2023.

[16]Meier, A., Shah, M., Toro Medina, J., Microgravity Experimentation of Long Duration Space Mission Waste Conversion. Presented at the 49th International Conference on Environmental Systems, ICES-2019-129, 7-11 July 2019, Boston, MA.

[17]Medina, J. A. T., Meier, A. J., Shah, M., and Rinderknecht, D. Waste Conversion to Usable Gases for Long Duration Space Missions. Presented at the ASCEND, 2020.

[18]Meier, A., Rinderknecht, D., Olson, J., Shah, M., Toro Medina, J., Pitts, R., Carro, R., Gleeson, J., Hochstadt, J., Forrester, E., Kruger, M., and Essumang, D. “Pioneering the Approach to Understand a Trash-to-Gas Experiment in a Microgravity Environment.” *Gravitational and Space Research*, Vol. 9, No. 1, 2021, pp. 68–85. https://doi.org/10.2478/gsr-2021-0006.

[19]Pitts, R. P., Rinderknecht, D., Olson, J. A., Shah, M. G., and Medina, J. T. Suborbital Testing of the OSCAR Trash-to-Gas System. Presented at the 51st International Conference on Environmental Systems, St. Paul, Minnesota, USA, 2022.

[20]Lewis, R. Exposure Guidelines (SMACs & SWEGs). *NASA*. http://www.nasa.gov/feature/exposure-guidelines-smacs-swegs. Accessed Jan. 5, 2023.

[21]Advanced Organic Waste Gasifier | SBIR.Gov. https://www.sbir.gov/sbirsearch/detail/1671045. Accessed Jul. 23, 2022.

[22]Shah, M. G., Pitts, R. P., Benson, M. A., and Gleeson, J. R. Investigating Waste Preparation Methods for Trash-to-Gas Technologies. Presented at the 51st International Conference on Environmental Systems, St. Paul, Minnesota, USA, 2022.

[23]Lockhart, L. Waste Handling in a Microgravity Environment Challenge | NASA. *Recycling in Space: Waste Handling in a Microgravity Environment Challenge*. https://www.nasa.gov/feature/recycling-in-space-waste-handling-in-a-microgravity-environment-challenge. Accessed Jan. 28, 2021.

[24]Teams | The Trash-to-Gas Ash Management Challenge | HeroX. https://www.herox.com/trashtogas. Accessed Jul. 24, 2022.

[25]Ewert, M.K. and Jeng, F.F., “Will Astronauts Wash Clothes on the Way to Mars?”, International Conference on Environmental Systems, July 2015, ICES-2015-53.

[26]Ewert, M.K., et al., “Clothes Cleaning Research for Space Exploration”, 51st International Conference on Environmental Systems, ICES-2022-391, 10-14 July 2022, St. Paul, Minnesota.

[27]Hooshyari, G., et al., “Demonstration of a Full-Size Integrated Greywater Recycling System Combining Biological Pretreatment with Reverse Osmosis”, 51st International Conference on Environmental Systems, ICES-2022-279, 10-14 July 2022, St. Paul, Minnesota.

[28] https://www.nasa.gov/chapea

[29] Vijapur, S.H., et al., “In-Situ Resource Utilization for Electrochemical Generation of Hydrogen Peroxide for Disinfection”, 49th International Conference on Environmental Systems, ICES-2019-38, Boston, MA, USA.

[30] Chen, T.T., Ewert, M.K., and Olson, J.A., “Benefits of Trash-to-Gas versus Jettison of Waste via Trash-Lock for Mars Transit”, 52nd International Conference on Environmental Systems, ICES-2023-047, 16-20 July 2023, Calgary, Canada.

[31] Momen, Ayyoub, et al., “Ground Testing of Full-Scale Direct Contact Ultrasonic Human Solid Waste Dryer with Enhanced Water Extraction Performance”, ICES-2024-287.

[32] Rini, E., Ewert, M.K. and Chen, T.T., “Integrated Waste Trade Study: Lunar Surface to Deep Space”, ICES-2024-92.

[33] Powell, C.D., Waguespack, G.M. and Ewert, M.K., “A Fecal Processing Technology Trade Study for Water Recovery in Various Mission Duration Scenarios”, ICES-2021-418.

[33] Boyce, S. P., et al., “Brine Processor Assembly: A Year of Successful Operation on the International Space Station,” ICES-2023-292, 52nd International Conference on Environmental Systems, 2023.

[34] Richardson, J., et al., “The Trash Compaction Processing System (TCPS) Technology Demonstrations and Risk Reduction Activities 2023-2024”, ICES-2024-163.

[35] Landwehr, A. and Ewert, M., “Equivalent System Mass (ESM) Factor Re-evaluation for Moon to Mars”, CTSD-ADV-2113, October 21, 2023.

[36] Lynch, C.S., et al., “Logistics Rates and Assumptions for Future Human Spaceflight Missions Beyond LEO”, AIAA ASCEND, 23-25 October 2023, Las Vegas, Nevada.