Mission Benefits Analysis of Logistics Reduction Technologies

Michael K. Ewert[1] and James Lee Broyan, Jr.[2]
NASA Johnson Space Center, Houston, TX, 77058

Future space exploration missions will need to use less logistical supplies if humans are to live for longer periods away from our home planet. Anything that can be done to reduce initial mass and volume of supplies or reuse or recycle items that have been launched will be very valuable. Reuse and recycling also reduce the trash burden and associated nuisances, such as smell, but require good systems engineering and operations integration to reap the greatest benefits. A systems analysis was conducted to quantify the mass and volume savings of four different technologies currently under development by NASA's Advanced Exploration Systems (AES) Logistics Reduction and Repurposing project. Advanced clothing systems lead to savings by direct mass reduction and increased wear duration. Reuse of logistical items, such as packaging, for a second purpose allows fewer items to be launched. A device known as a heat melt compactor drastically reduces the volume of trash, recovers water and produces a stable tile that can be used instead of launching additional radiation protection. The fourth technology, called trash-to-gas, can benefit a mission by supplying fuel such as methane to the propulsion system. This systems engineering work will help improve logistics planning and overall mission architectures by determining the most effective use, and reuse, of all resources.

Nomenclature

ACS	=	advanced clothing system
AES	=	Advanced Exploration Systems
CTB	=	cargo transfer bag
ESM	=	equivalent system mass
HMC	=	heat melt compactor
ISS	=	International Space Station
LRR	=	Logistics Reduction and Repurposing
L2L	=	logistics-to-living
LTL	=	logistics-to-living
MCTB	=	multi-purpose cargo transfer bag
NASA	=	National Aeronautics and Space Administration
SE&I	=	systems engineering and integration
TRL	=	technology readiness level
TtG	=	trash to gas

I. Introduction

THE Advanced Exploration Systems (AES) program's Logistics Reduction and Repurposing (LRR) project is continuing its second year of a three year technology development. Logistical supply needs are strongly correlated with space mission duration, and innovative ways of reducing, reusing, repurposing, and reconstructing materials are required. The interrelationship of how a reduction in mass or volume or planned reuse of an item for a secondary purpose requires a strong systems analysis component to ensure the benefits are understood. Clear

[1] AES Logistics Reduction and Repurposing Project Manager, Crew & Thermal Systems Division, 2101 NASA Parkway, Houston, TX, 77058/Mail Stop EC7, not AIAA affiliated.
[2] AES Logistics Reduction and Repurposing SE&I Lead, Crew & Thermal Systems Division, 2101 NASA Parkway, Houston, TX, 77058/Mail Stop EC2, not AIAA affiliated.

understanding is required to enable the vehicle and mission architecture to take advantage of these potential benefits. For example, if residual logical material and waste volume can be significantly reduced as the mission progresses, the increase in habitable volume may allow a smaller initial vehicle volume (or more equipment). It is also important to understand when a repurposed item becomes available compared to when the function is required in the mission. The LRR project involves six NASA centers developing four technologies that contribute to an overall reduction in exploration logistical mass and volume. Of course, logistics reduction is a very broad area for research and highly integrated into specific mission decisions (resupply options and crew size), technology selections (life support closure), and hardware decisions (consumables and spares approach). LRR's strategy is to develop technologies that are not uniquely tied to specific mission, technology, or hardware decisions, but to develop approaches that can improve or enable new ways to reduce logistics and improve crew habitation. The four LRR technologies cover a range of technology readiness levels and each addresses one of the typical reduce, reuse, repurpose, and reprocess approaches to waste reduction. The LRR technologies being developed are described by the following major tasks:

- Evaluation of antimicrobial treatments as part of an advanced clothing system (ACS) to enable clothing to be worn longer, thereby directly reducing consumable mass.
- Development of launch packaging containers and other items that can be repurposed on-orbit as part of habitation outfitting in a logistics-to-living (L2L, or LTL) concept.
- Design and development of hardware for processing trash into compact and stable tiles via heat melt compactor (HMC) processing.
- Research into the conversion of trash to gas (TtG) for high levels of volume reduction and to produce gas for venting or propulsion.

The general approach and benefits of the four technologies have been previously described[1]. The focus of this paper is to provide a more detailed discussion of the development of the logistical and waste models and the mission benefits of these four technologies. Recent[2,3], concurrent[3.5,4,4.5] and future papers describe the specific technologies and their development progress.

II. Logistics and Waste Model for Exploration Missions

In 2012 the LRR project developed version 1.0 of a logistics and waste model for human exploration missions[1] (2012 ICES paper). The model included mass of the consumables that are required to support four crewmembers for 1 year away from Earth, based heavily on ISS data. However, some projections beyond ISS were made for exploration missions, such as reductions in disposable batteries, ink and paper. Four is considered the most likely crew size for near term exploration missions. Other characteristics of these missions are micro-gravity, limited extra-vehicular activity, and need for high reliability systems since immediate return to Earth is difficult or impossible.

The Logistics Model has been updated to version 2.0 in 2013 with the addition of volume information, detail on the major elemental composition of the waste stream, increased considerations for logistical packaging materials, and other minor updates. The model focuses on logistical supplies directly supporting the crew and life support systems and includes over 50 line items. These consumables are divided into several broad categories, and mass and volume of each are shown in Figures 1 and 2. Crew Provisions (colored red) includes clothing, hygiene and other crew supplies. The Food System (colored blue) includes food, food packaging and food storage containers. EVA and medical systems supplies are grouped together (colored green). Collectively these 3 categories are called "Crew Consumables". Adding to that a less developed category called "Life Support System Supply" gives us total "crew-related consumables". Life Support System Supply (colored yellow) includes air, water and waste system filters and other consumable items, but not the mass and volume of the permanent life support systems themselves. These systems are assume to be based on current state-of-the-art ISS regenerative life support systems. Total mass and volume of all the crew-related logistics add up to __ kg and __ m^3 for a crew of 4 over a year. Fluids such as water and oxygen were not included because they can vary greatly depending on mission and life support technology decisions. However, it is hoped that most exploration mission will take advantage of closed-loop life support technology and thus require minimal life support fluids to be launched.

Food represents the largest crew consumable. Food is launched in several states including natural/fresh form, freeze dried (requiring hydration prior to consumption), and thermosabilized. There is food research by the Human Research Program into nutritionally appropriate, caloric dense foods, with long shelflife and reduced packaging. The LRR project will update the logistics model as advances are made in this area.

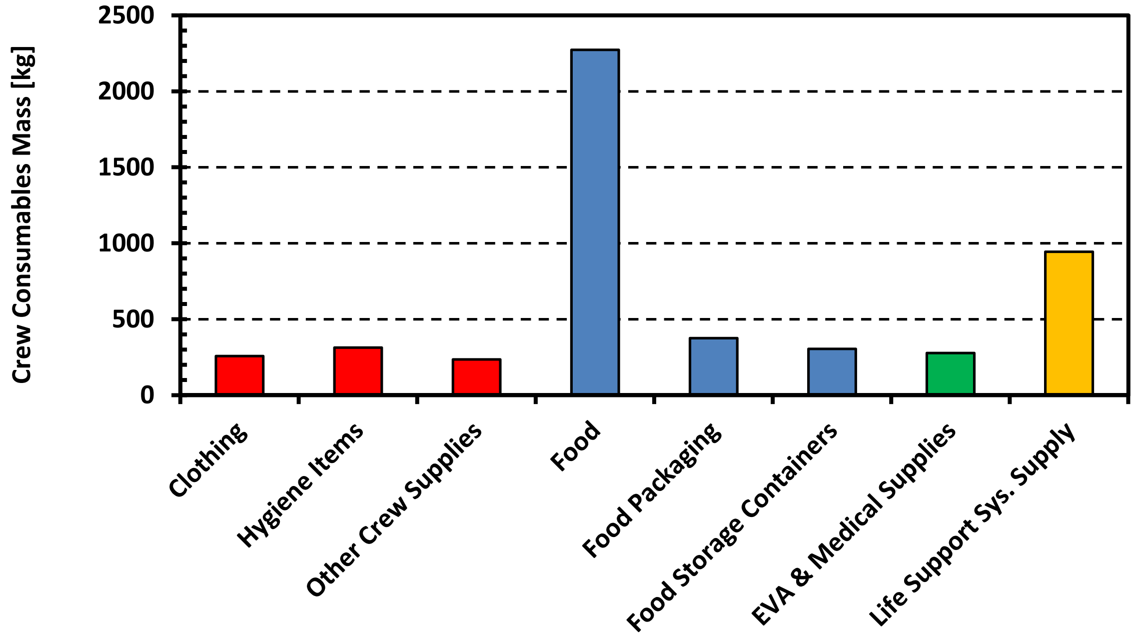

Figure 1. LRR crew-related consumables mass for a four-person crew on a one-year mission.

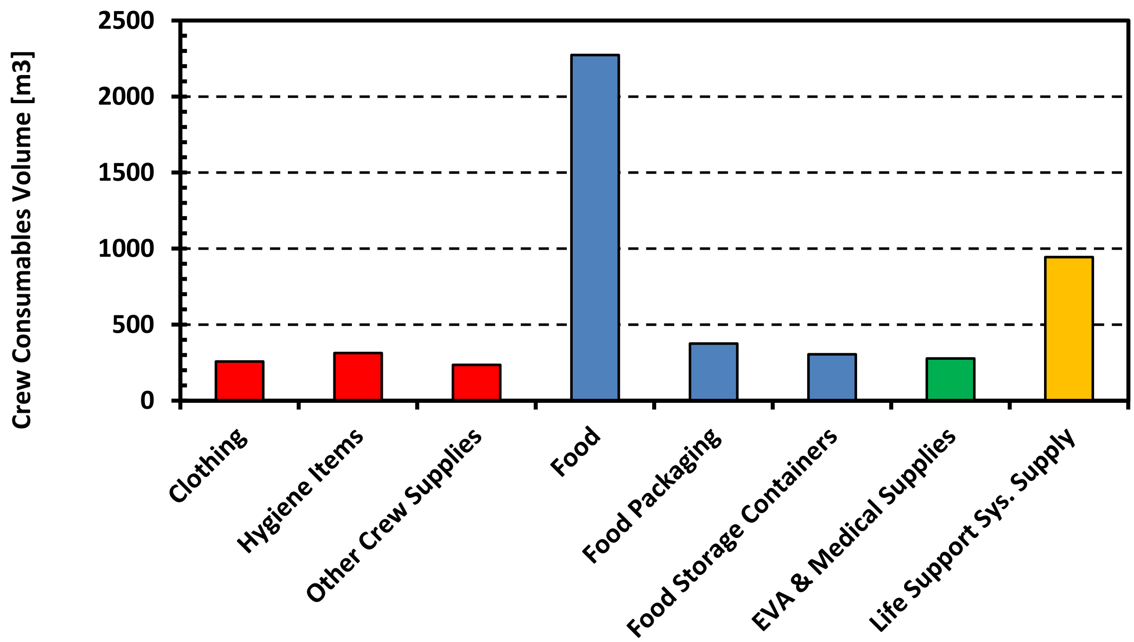

Figure 2. LRR crew-related consumables volume for a four-person crew on a one-year mission.

These estimates of logistics launched also form the basis of mission analysis on how they are used by the crew and what becomes waste that requires disposal. Thus a companion waste model has also been created as part of the LRR Logistics Model 2.0. Results are shown on a mass basis in Figure 3 for the same 4 person crew for a year. Crew consumables waste mass totals 1823 kg and life support system consumables waste mass is 788 kg, for a grand total of 2611 kg of crew-related waste mass. Assumptions were made about how the logistical items are used and which portions become waste products. Particularly complex are food assumptions. A small portion of the food and its residual water is wasted due to container residue or uneaten portions. However a substantial portion is transformed into human waste products such as carbon dioxide, sweat, urine and feces. Of these, the carbon dioxide and water are treated as life support system resources assuming state-of-the-art technologies, and only the left over brine (15% of urine + flush water stream) and feces are shown as waste resources. Since many items, such as clothing and wipes, will still be in use or perhaps some left over at the end of the mission (due to contingency planning), 10 or 20% of these items did not enter the waste stream. No clothing laundry system was assumed in the baseline model because a one year mission is likely not long enough for the benefits of laundry to significantly exceed the direct clothing mass.

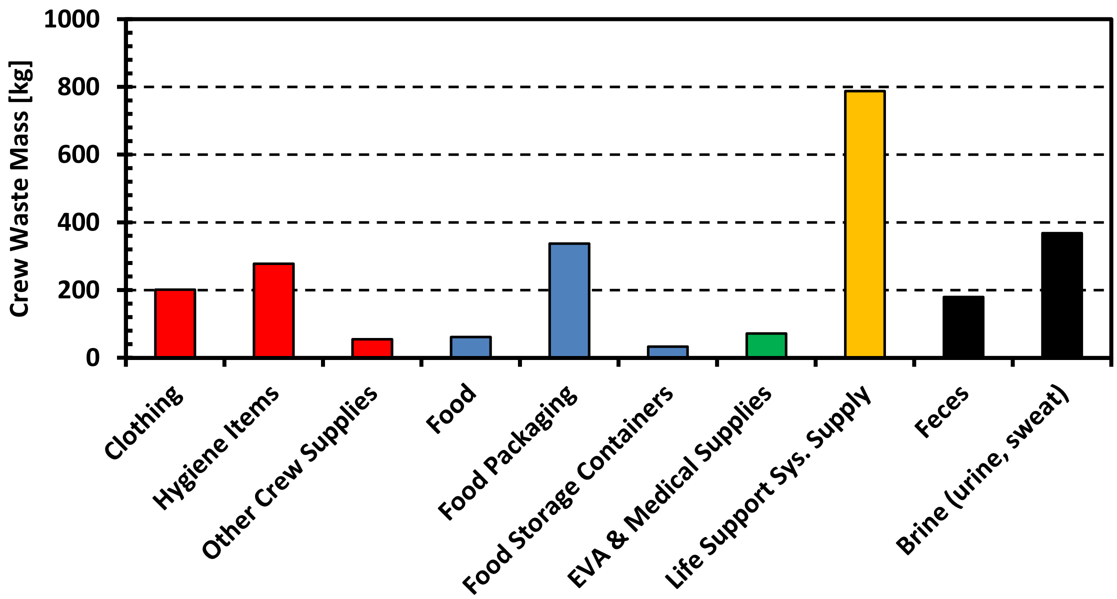

Figure 3. LRR crew-related waste model for a four-person crew on a one-year mission.

Further definition of this waste stream was then undertaken by examining each line item's major materials of construction. The major elemental composition was calculated or estimated as a mass percentage. These percentages could then be multiplied by the item's total mass in a spreadsheet and easily updated if the waste model quantities change. Total percentages by mass for the "Crew Consumables" waste stream are shown in Figure 4. Life support system wastes (e.g. filters, fecal containers; *yellow bar in Figure 3*) are not included in Figure 4 since it is not yet known how much of this can be recovered. Some items contain metal or toxic chemicals, so this is an area for future work.

The elemental composition is particularly important to technologies such as TtG, which chemically decompose the waste. Since water may be recovered directly in technologies such as HMC, percent water was also computed in addition to the full elemental decomposition and is shown in Figure 5.

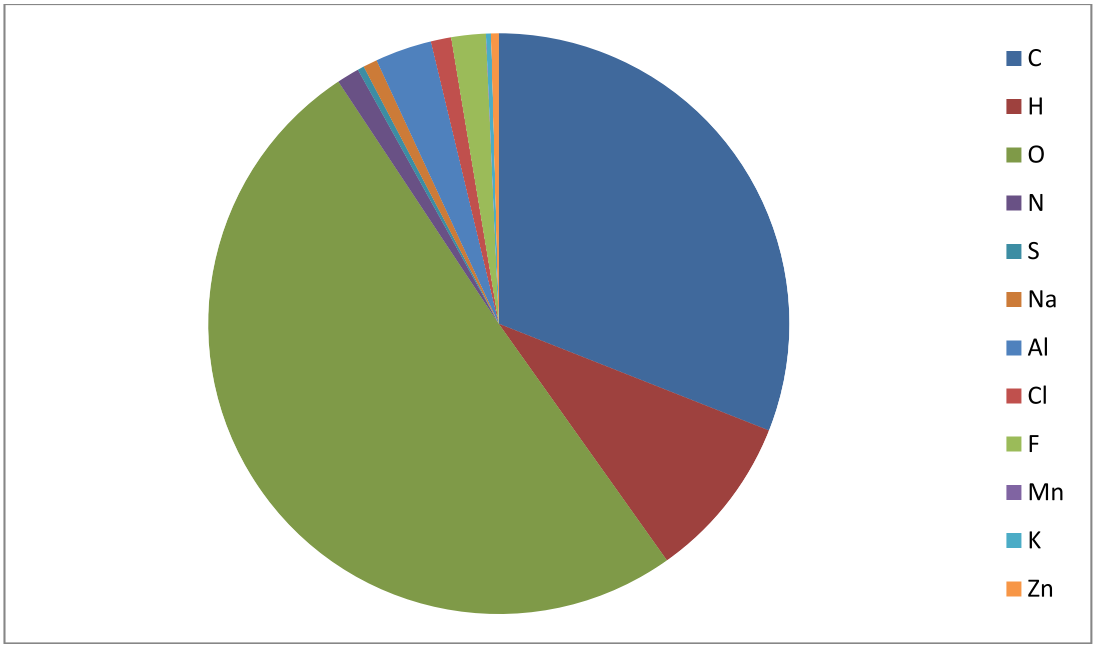

Figure 4. Elemental composition of crew consumables waste stream.

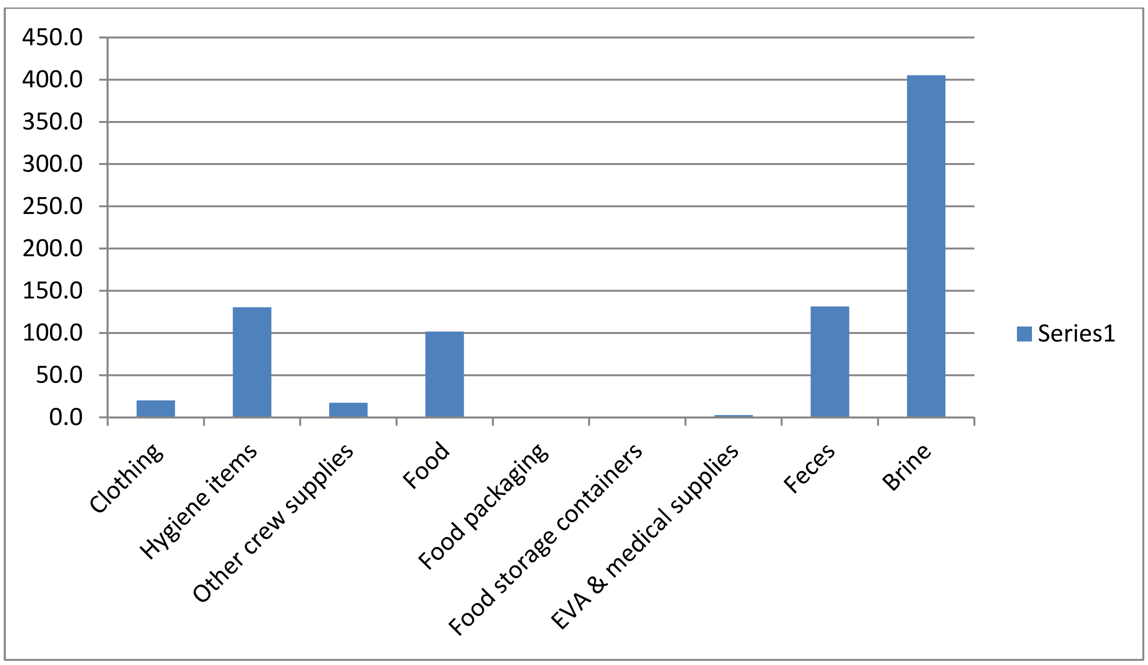

Figure 5. Water contained in crew consumables waste stream (kg).

III. Systems Analysis of Technology Benefits

Each of the 4 technologies under development by the AES LRR project have benefits to future human exploration missions. The sections below describe these benefits and compare them to state-of-the-art as much as possible. Since mass, power, cooling, volume and crew time are all precious resources on space missions, quantifying these for affected hardware and consumables is the first step. An equivalent system mass (ESM) technique developed by NASA's Advanced Life Support project can help reduce all these factors to a common metric for a given mission, and future LRR trade-off studies will use this method.[5.] Since several different future human missions are still under investigation within NASA, private industry and the international space community, the approach taken in this paper is to analyze the generic mission covered by the Logistics Model 2.0, described above. Basically, what is required to support a 4 person crew in deep space for a year? Fortunately, this is similar for most of the missions under discussion (e.g. asteroid, L2 station for lunar return or other purposes, Mars). We do assume micro-gravity, no resupply, limited EVA, need for station-keeping or other thrusters and a deep space radiation environment. Subsequent studies can easily adapt the results below to specific missions, which may deviate from these assumptions for at least part of the mission.

A. Advanced Clothing Systems

Since a washing machine has not yet been developed for micro-gravity use, clothing on ISS is worn as long as it is tolerable to the crew based on smell and 'crustiness'. Typical usage rates for different articles of clothing can be found in reference 6. Mostly cotton, commercially available clothing is currently used. Clothing is an important aspect to crew comfort and crew acceptance of items is a strong consideration. The LRR project is investigating different fabric types and anti-microbial treatments that could reduce mass and/or increase wear time. The intent is to find acceptable antimicrobial treatments that can be applied to commercial clothing. Trade studies of advanced clothing without laundry are fairly simple to calculate if the wear data is available since power, cooling and crew time are not factors. Mass and volume of the clothing used during the one year mission can simply be compared for the baseline ISS case and the 'advanced clothing' case. An LRR ground test of clothing treatment Bio-Protect 500 is scheduled for March - May 2013 and will include about 100 participants and multiple fabrics and controls. According to the manufacturer, Pureshield, Inc. (http://bio-protect.net/about/), "Bio-Protect 500 creates a Micro-biostatic Antimicrobial Coating on the surface that inhibits odor causing bacteria, mold and mildew." Since the test results were not available at the time of this writing, reductions due to longer wear cannot be calculated yet.

Polyester, mod-acrylic, wool and cotton shirts and polyester and cotton shorts are being considered for exercise clothing in the ground evaluation. In the current Logistics model 26 exercise shirts and 52 pair of exercise shorts are required for our generic mission. The mass comparison with the baseline cotton exercise shirts and shorts is seen in Table 1. Even though the current cotton clothing is flammable, polyester is considered worse due to its melting characteristics. Thus, the current strategy is to try and replace only limited use exercise clothing with polyester and look at other options for general wear clothing. Thus, there are 2 ways that ACS savings can increase compared to the projections in Table 1: 1) longer wear due to anti-microbial treatment and 2) substitution of additional clothing items with lighter weight options.

Table 1: Mass and Volume Comparison between ISS cotton and 'Advanced' polyester exercise clothing for a 4 person crew on a one year mission.

Clothing item	ISS usage (days)	ISS mass (kg ea)	ACS mass (kg ea)	# per yr	ACS savings (kg/yr)
Exercise shirts	14	0.30	0.143	26	16.3
Exercise shorts	7	0.15	0.127	52	4.8
TOTAL					21.1

B. Logistics to Living

As described in reference 2, a leading idea for Logistics to Living (L2L) is to repurpose Cargo Transfer Bags (CTB's) after launch to fulfill other functions such as privacy partitions and sound absorbing blankets. The possibility of using repurposed CTB's to form the entire crew quarters of a space habitat is also being explored. On ISS, CTB's are used extensively to contain clothing, other crew provisions, and to protect sensitive hardware against launch acceleration and vibration. While it is possible that alternative methods of stowage will be developed for future exploration missions, it is likely that current CTB practices will continue. The number of CTB's in the Logistics Model 2.0 is shown in Table 2. Since so many are used to contain food during launch, this represents the best opportunity for direct mass and volume reductions or repurposing opportunities.

Table 2: Cargo Transfer Bag Characteristics in Logistics Model 2.0

Type	# of CTB's	Unit mass (kg)	Total mass (kg)	Unit vol. (m^3)	Total vol. (m^3)
For crew provisions	25	1.9	47.5	0.0064	0.16
Crew preference & care	6	1.9	11.4	0.0064	0.04
For food	141	1.9	267.9	0.0064	0.90
TOTAL	172		327		1.1

The LRR L2L team has designed and built prototypes of a multi-purpose cargo transfer bag (MCTB), which is functionally equivalent to the ISS CTB's but has zippers and snaps which allow it to unfold into a flat rectangle. After they have been used to contain supplies during launch, the MCTB's can be repurposed, thus saving the mass and volume of items they replace. The MCTB's should weigh approximately the same as the current CTB's. Power and cooling are not applicable since the MCTB's require none. Some crew time will be required to reconfigure the MCTB's for their new purpose, so this should be taken into account if dedicated partitions could have been pre-installed prior to launch.

The secondary functions that MCTBs can provide need to be prioritized and compared to the mission timeline for when those functions are required. It is anticipated that early in the mission a relatively large number of MCTBs will be available as the sensitive equipment is unpacked and installed. But this may not provide all the MCTBs required. Additional MCTBs will become available at a fairly steady rate as consumables are used.

Current estimates by the LRR L2L team suggest the quantities and purposes in Table 3 for repurposed MCTB's. If all of these can be realized, the total mission (4 crew, 1 year) mass and volume savings will be 146 kg and 0.5 m^3.

Table 3: Estimated Reuse Potential for Multi-purpose Cargo Transfer Bags on a 1 Year, 4 Crew Mission

Repurposing potential	# of MCTB's	Potential mass savings (kg)	Potential volume savings (m^3)
Room partitions	9	17.1	0.06
Sound absorbing blankets	4	7.6	0.03
Crew quarters	16*4=64	121.6	0.41
TOTAL	77	146	0.5

C. Heat Melt Compactor

1) **Trash Processing** in the Heat Melt Compactor (HMC) provides several benefits, as described in reference 7. The benefits quantified here are mass and volume of water recovered, volume recovered due to compaction of the trash and potential mass saved by a reduction in the dedicated radiation shielding. Savings accrued will be proportional to the amount of trash that can be processed in the HMC, so all items in Logistics Model 2.0 were evaluated for their suitability for processing. Mainly, rigid metallic items were excluded due to the risk of scratching the nonstick surface of the HMC chamber and feces were excluded. At this time the HMC has not yet been evaluated for fecal processing. MCTB's were also excluded, preserving them for reuse by L2L; however, excess MCTB's could be processed in the HMC,.

As described in reference 7, estimates for the amount of trash that will be generated on exploration missions can vary quite a bit. Thus a 'base case' matching Logistics Model 2.0 as well as a 'maximum case' from reference 7 are both considered in the benefits analysis below. As described above, the base case yields 1073 kg (per year for a crew of 4) of trash suitable for processing in the HMC. Compare this to the 2611 kg of total crew-related wastes in Figure 3 above. From the Model 2.0, the average composition of the trash is:

27.2% water and

34.6% plastic.

These percentages are used for both base and maximum cases and do not include urine brine. Brine processing is a special case that is discussed below. Based on dimensions from the HMC generation II design review, each run can process 1.5 kg of wet trash with an average hand-compacted density of 84 kg/m^3 and a chamber volume of 0.018 m^3. This means that 2 runs per day would be required to process all the trash in the Model 2.0 base case. The HMC can apply a pressure of approximately 50 psi, which generally results in a 10:1 volume reduction, but of course this varies with trash composition. Using the numbers above the benefits shown in Table 4 were computed for the generation II HMC.

2) **Brine Processing** is possible with the HMC because the HMC is capable of evaporating and condensing the water. Brine processing is currently not a funded requirement of the HMC, but some preliminary conceptual and feasibility work has been performed previously[8]. ISS brines and future brines are likely to classified as hazardous fluids due to the urine pretreatment chemicals or the concentrated urine itself. Hazardous fluids require multiple levels of containment depending on their classification. The brine would be transferred from the urine processor recycle loop to a flexible polymer bag containing a substantial surface area of gas permeable membrane. The brine bag would be placed into the HMC trash processing chamber. The brine bag would be required to provide the necessary levels of containment for the brine so that the HMC would not be damaged or contaminated by an inadvertent leakage of fluid. The HMC would likely reduce its chamber pressure to reduce the temperature for brine vaporization. The HMC would only apply a very low level of compaction to maintain thermal contact between the

bag and the chamber heated surfaces. Water vapor would be condensed by the same HMC hardware used for trash processing. Brine processing would require ~24 hours due to power limits available for normal trash processing and so as to not exceed the HMC condensation capability. The brine bag would then be removed and discarded and normal trash processing could resume. Further development of the brine bag is not planned at this time but it represents an additional way to improve water loop closure for future vehicles and would result in the benefit shown in Table 4.

Table 4. Benefits of generation II Heat Melt Compactor for various cases (4 crew, 1 yr. mission).

Benefit/ parameter	**Base case**	**Max. case**
Mixed, wet trash to process	1073 kg	1610 kg
Water recovered from trash	289 kg	433 kg
Volume recovered from trash	8.4 m^3	12.7 m^3
Volume of HMC	0.13 m^3	0.13 m^3
Net volume savings	8.3 m^3	12.6 m^3
Number of 0.23cm x 0.23cm radiation tiles produced	769	1154
Mass of radiation tiles produced	784 kg	1176 kg
Mass of HMC	80 kg	80 kg
Net mass savings (excluding brine processing)	993 kg	1529 kg
Energy required to process trash	620 kWh	913 kWh
Urine brine to process	342 kg	
Water recovered from urine brine	274 kg	
Energy required to process urine brine	215 kWh	

D. Trash to Gas

Trash to Gas (TtG) technologies can process most items since they generally decompose the trash in a thermo-chemical process. In the Logistics Model 2.0 it is estimated that 1917 kg of the 2611 kg total waste stream can be processed by TtG. For a complete list of technologies under consideration by the LRR project, see reference 8. A down-selection to the most promising technologies based on small scale testing and analysis is scheduled for fiscal year 2013, so more detailed analysis will be possible soon. Since the processes are similar, the approach taken here is to use a generally representative process for 3 separate cases of desired output:

1) Methane production
2) Gas production for resistojets
3) Gas production for non-propulsive venting

Different TtG technologies may trade better for these different cases, so that will be taken into account in the down-selection process, and refined as mission details become available. Case 1 will save mass and volume where oxygen/methane rocket engines are used, and case 2 will save mass and volume for any mission that requires station-keeping thrusters. Case 3 will not have mass and volume savings benefits to the propulsion system, but, like cases 1 and 2, will have the advantages of trash volume reduction and odor control. All 3 cases also avoid the difficulties associated with trying to store the trash for long periods of time or jettison it to space.[9] Energy requirements for each case and each technology will be different and will be the subject for future work.

A system mass balance analysis was conducted to quantify the amount and composition of gases for each of the 3 cases above and the generic results are shown in Table 5 below[10]. Reactants such as oxygen or water need to be supplied to some of the processes to close the mass balance, so these must be taken into account in the net benefits analysis. After technology down-selection is made in 2013, the “representative technology” numbers can be refined for specific technologies for each of the 3 cases. Down-selection criteria will include quantity of useful gases generated from a representative trash source, breadth of materials that can be processed and mass, power and volume resources required for the system. All candidates must also be able to meet spacecraft safety requirements.

IV. Conclusions

The AES LRR logistics and waste modeling described here provides a means of quantifying cradle-to-gave mission benefits analysis. The four current LRR technologies represent a broad range of reduce, reuse, repurpose, and reformulate approaches. The mission benefits analyses to-date are a good indication of the types of savings that are possible, including ≥ 21 kg/yr for ACS, 146 kg/yr for L2L, 1267 kg/yr for HMC, and 2413 kg/yr for TtG-type technologies. All these savings may not be additive since some depend on the same waste stream; however, it is conceivable that trash could be processed in the HMC to recover water, producing radiation shielding tiles that could be used for the majority of a mission and then processed again by TtG to yield propellant for a final burn. As exploration missions are defined in detail and as the LRR technologies provide performance data, this cradle-to-grave analysis will be periodically repeated to allow adjustment of the four LRR hardware work plans. In addition, the analysis results will enable development of requirements and design features required of logistical components to enable effective reuse on-orbit. For example certain materials might be excluded from the logistics composition so that later reuse can be increased.

Table 5. Gases produced and resources required for representative Trash to Gas technology (4 crew, 1 yr. mission).

Benefit/parameter	**1)Methane**	**2)Gas-resisto**	**3)Gas-vent**
Mixed, wet trash to process (without urine brine)	1701 kg	1701 kg	1701 kg
Water required into the system**	757 kg	0 kg	0 kg
Volume recovered from trash			
Volume of TtG system			
Net volume savings			
Energy required for TtG process	TBD	TBD	TBD
Mass of methane recovered (including from crew CO2)	1350 kg		
Mass of oxygen recovered	1920 kg		
Total mass of gases recovered (not counting water)	3270 kg	2515 kg	2515 kg
Mass of TtG system	100 kg	100 kg	100 kg
Net mass savings due to propellant recovery	2413 kg		0 kg

** methane and oxygen are maximized at the expense of water

The generated detailed data are essential to the rigorous systems analysis that will optimize how material recycling occurs on future long-duration missions. Mass, power, volume, thermal control, and crew time trade studies will be conducted to support programmatic decisions since these parameters often compete with each other. The detailed Logistics Model 2.0 and initial quantification of technology benefits for a generic one year mission presented here provide a sound basis for these future trade off studies as specific human exploration missions are defined.

Acknowledgments

This paper summarizes the work that was performed by numerous Ames Research Center, Glenn Research Center, Johnson Space Center, Jet Propulsion Laboratory, Kennedy Space Center, and Marshall Space Flight Center engineers, analysts, functional specialists, technicians, and crew members. The AES LRR project is funded by the NASA Headquarters Advanced Exploration Systems Division.

References

1. Broyan, J. L., Ewert, M. K., "Logistics Reduction and Repurposing Beyond Low Earth Orbit", 42nd International Conference of Environmental Systems, AIAA, 2012.

2. Shull, S., et al., "NASA Advanced Exploration Systems: Concepts for Logistics to Living", Space 2012, Pasadena, CA, AIAA, 2012.

3. Hintze, P., et al., "Trash to Supply Gas (TtSG) Project Overview", Space 2012 Conference, Pasadena, CA, AIAA, 2012.

3.5 Pace, G., et al., "Design limits of the Heat Melt Compactor for processing of Solid Wastes", 43nd International Conference of Environmental Systems, AIAA, 2013.

4. Turner, M., et al.., "Gen 2 Heat Melt Compactor Development", 43nd International Conference of Environmental Systems, AIAA, 2013.

4.5 Caraccio, A. and Hintze, P., "Trash-to-Gas: Converting Space Trash into Useful Products," 43rd International Conference on Environmental Systems, AIAA, 2013.

5. NASA/TM—2003-212278, "Advanced Life Support Equivalent System Mass Guidelines Document", Levri, J., et al.

6. Ewert, M. K., Jeng, F. F., "Lundry Study for a Lunar Outpost", 2009-01-251, 39th International Conference on Environmental Systems, SAE International, 2009.

7. Jones, H., Pace, G. and Fisher, J., "Managing Spacecraft Waste Using the Heat Melt Compactor (HMC)", 43nd International Conference of Environmental Systems, AIAA, 2013.

8. (Lance Delzeit's 2012 paper)

9. Diane's paper?