Space Mission Utility and Requirements for a Heat Melt Compactor

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Management of waste on long-duration space missions is both a problem and an opportunity. Uncontained or unprocessed waste is a crew health hazard and a habitat storage problem. A Heat Melt Compactor (HMC) such as NASA has been developing is capable of processing space mission trash and converting it to useful products. The HMC is intended to process space mission trash to achieve a number of objectives including: volume reduction, biological safening and stabilization, water recovery, radiation shielding, and planetary protection. This paper explores the utility of the HMC to future space missions and how this translates into HMC system requirements.

Nomenclature

ARC	=	Ames Research Center
a_w	=	Water activity
BFO	=	Blood-forming organs
cGy	=	Centigray=1/100 of the absorption of one joule of radiation energy per kilogram of matter
CM	=	Crew member
CMU	=	Compress Melt Unit
CTB	=	Cargo Transfer Bag
GCR	=	Galactic Cosmic Radiation
Gen1	=	1st generation HMC
Gen2	=	2nd generation HMC
HEOMD	=	Human Exploration and Operations Mission Directorate
HMC	=	Heat Melt Compactor
JSC	=	Johnson Space Center
NAC	=	NASA Advisory Council
PE	=	Polyethylene
PMWC	=	Plastic Melt Waste Compactor
RFI	=	Request for Information
SPE	=	Solar Particle Event
SMD	=	Science Mission Directorate
TOC	=	Total organic carbon
UPA	=	Urine Processing Assembly

I. Introduction

THE development of the Heat Melt Compactor began about 2003. It was desired to develop a technology that could be used for reducing the volume of trash on space missions and to make the reduced volume trash stable such that it did not reexpand in volume, did not support microbial growth, and did not release contaminant gases to the cabin - that the waste would be volume minimized and stable. Looking for the simplest technology that could provide these advantages led to consideration of the heat melt compactor (HMC). By its very nature the HMC produces water vapor, melts the plastic, and produces hard dense tiles. These characteristics lead to the other advantages of the HMC – water recovery, radiation shielding, and planetary protection.

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The paper first presents background developmental history and operational characteristics. Each of the utilities or benefits is then examined in some detail. In order to achieve the desired utility, the HMC hardware must satisfy function and hardware requirements. Knowledge obtained from the development effort was used to determine the requirements, and key requirements are summarized in this paper.

II. Background

A. History

Development of solid waste management systems generally has been conducted by NASA at least as far back as the mid-1980s. Reference 1 contains a summary of NASA waste management technology development in the 1990s. Development of a mechanical trash compaction system by NASA goes back at least as far as 1990, and development of a heated mechanical trash compaction system began in 2003. Numerous papers have been written on the development of a heat melt compactor (HMC) since 2003.[2-21]

At least two compaction systems were considered by NASA before the HMC. On the Shuttle flight STS-35 in 1990 a manual mechanical compactor was tested in space. This system was unheated. It used a special cylindrical bag with straps on the ends to prevent spring back. This compactor used two opposing hand operated grips to drive the compaction. Unfortunately one of the grips broke off early in the testing. This system was not adopted for continued use on later shuttle flights. Figure 1 shows the STS-35 compactor on flight. A second investigation of unheated compaction for NASA flights was conducted by Oceaneering International, Inc. The trash was compacted into a square bag, which also had straps to prevent spring back. The Oceaneering effort investigated a scissors link system, a telescoping ball screw, a three ball screw system, a cabin air actuated system, and a hydraulic system. This investigation found the scissor link system to provide the most practical and efficient means of exerting the required force to effectively compact trash. This system was tested on trash from the 1992 STS-42 Shuttle flight.

Figure 1. Manual compactor tested on STS-35

In 2003 investigation of a compaction system for future long-duration space missions was begun at NASA Ames Research Center (ARC). An unheated compactor may have been sufficient for Shuttle, but on future long-duration missions large amounts of stored wet trash are a health hazard and the water in the trash is a valuable resource that can be recovered. If the trash is heated above the melting point of plastic (roughly 130 C for polyethylene), then not only can the water in the trash be driven off, but the melted plastic in the trash provides a means for encapsulating the trash and preventing spring back when the compacted trash is cooled. These were the initial drivers behind investigating a heated trash compactor.

A review of alternatives in 2003 identified a heated trash compaction system that was used by the Navy for compacting trash on board naval surface ships. This system is called the Compress Melt Unit (CMU). Commercial versions of the CMU are available today. Figure 2 shows a picture of a current CMU which is very similar to the unit that was in used by the Navy in 2003. Although the Navy's CMU was a type of heat melt compactor, it vented water and gas to the atmosphere. For space application it is desirable to recover the water and to control the contaminants produced by the process because venting to space implies a loss of valuable gases. In addition, a space mission heated compactor has to operate in microgravity. ARC began an experimental investigation to produce an HMC, which was initially called the Plastic Melt Waste Compactor (PMWC). Figure 3 shows the initial benchtop setup used to test compaction forces and temperatures required to produce acceptable compacted trash pucks. The setup included a heated oven with a shaft and platform on the top on which weights could be placed to produce pressure.

Design of the first prototype HMC was begun in 2005 and fabrication and assembly was begun. However, a redirection of research led to a pause and a temporary redirection of the compaction development. In 2007 an unheated compactor was developed for possible application to the Crew Exploration Vehicle (or Orion as it is called
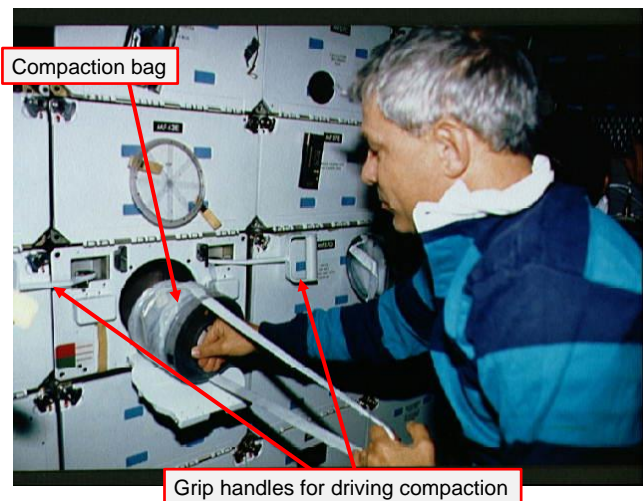
today). Here the objective was similar to the compactors tested on Shuttle: simply reduce the volume of the trash. Figure 4 shows the unheated compactor prototype. The compaction chamber is about 51cm-18cm-18cm with a small external air pump (15cm-8cm-8cm) for the pneumatic ram. It had a specially designed trash bag designed to absorb any water that might be squeezed out of the trash and prevent it from escaping back into the cabin.[13]

Figure 2. Compress Melt Unit – commercial system similar to one used by the Navy in 2003
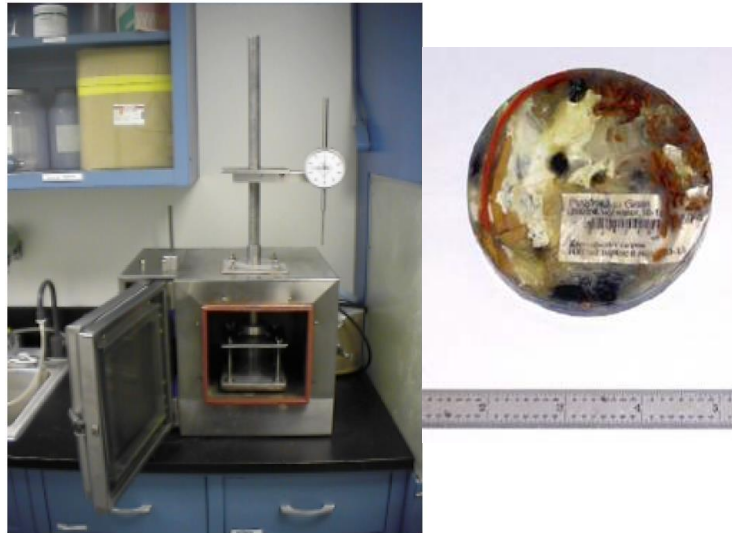

Figure 3. Heated vacuum oven used for benchtop testing in 2004 and an example 3 inch test trash puck produced.

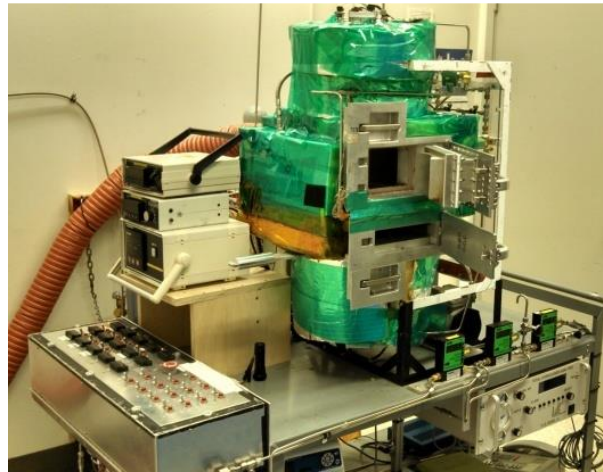**Figure 4. Unheated CEV compactor from 2007.**

Figure 5. Gen1 HMC initially assembled in 2008 and tested until 2013.

In 2008 assembly of the Gen1 HMC was completed and testing began. This unit uses a pneumatically driven ram that compacts with 50 psi (345 kPa) force and produces 20.3 cm diameter by 2.5 cm thick circular tiles. Testing continued intermittently until 2013. Tests evaluated density of tiles, concentration of contaminants in the off gases, effectiveness of catalytic oxidation of off gas contaminants, effects of different types of trash inputs, different types of control schemes, effectiveness of microbial control, quality of water produced, use of tiles for radiation shielding, and other process parameters. Figure 5 shows the Gen1 HMC hardware. Figure 6 shows tiles made by the Gen1 hardware.

A Plastic Melt Waste Compactor (PMWC – another version of an HMC) was produced via a Phase II SBIR by Orbital Technologies, Inc. (Orbitec). This unit included a different method of compaction chamber venting (through vent nozzles rather than around the ram as was done for the Gen1 and Gen2 HMCs) and included surface coatings to reduce sticking of the trash to the walls. It compacts with about 12 psi (82.7 kPa) and produces 40.6 cm by 40.6 cm

by 3.8 cm square tiles. It was tested both by Orbitec and delivered to and tested by NASA ARC in 2014. Figure 7 shows the Orbitec unit.

Figure 6. Gen1 Tiles. General trash on left, ISS packing foams in middle, Bosch carbon on upper right.

Figure 7. Orbitec phase II SBIR PMWC.

In 2012 the project to produce and test the Gen2 HMC began. It is intended to be flight like and to address the requirements for a test in an Express Rack on International Space Station (ISS). It makes square tiles 9 in. x 9 in. x 1 in. (22.9 cm x 22.9 cm x 2.54 cm). The basic enclosure is sized for a double ISS rack, the control software is compatible with ISS, and all of the components needed for processing, collecting water, and venting to cabin are integrated together. The system includes the core unit, a separator to prevent squeezed out water from reaching the condenser, a condenser and phase separator system, and a trace contaminant control system. It is not fully flight capable because the phase separation on Gen2 is gravity dependent, the electrical control system is not miniaturized, the components in general are not fully optimized and sized for a flight system, and the condensation and contaminant control systems are spread out to facilitate ground testing. Microgravity condensation and separation has been evaluated and some experimental options explored,[22-24] but microgravity condensation and separation hardware is not yet available for integration with the Gen2 hardware. The compactor ram is a scissor link drive instead of the pneumatic system of Gen1. To date the system has been fully fabricated, fully assembled, and partially checked operationally. Figure 8 shows the Gen2 hardware.

Figure 8. Gen2 HMC Hardware.

B. Waste Model Used for Testing

Conducting tests of the HMC hardware requires preparation of trash samples to test the system. A simulant is used most of the time since samples of Shuttle or ISS trash are difficult to acquire. In addition, the trash for future long-duration missions can vary from that on Shuttle or ISS. Studies have been conducted regarding what can be expected in the trash on future missions, and based on these studies a simulant has been determined that represents the average composition of trash that would be present on a future space mission. Table 1 below shows the overall composition of the simulant that is used. Table 2 shows the breakdown of the food content in the simulant.

Table 1. Simulant for overall composition of average future mission trash for input to HMC.

Trash batch constituents	gm in 500 gm trash batch	percent of trash	approx. water content fraction
Cotton T shirt	84.2	16.83	0.06
Towels	37.1	7.41	0.06
Computer paper + food packaging paper	6.2	1.24	0.06
Dry lab chem wipes	14.0	2.81	0.06
Huggies (wet wipes)	29.1	5.81	0.70
Nitrile gloves	11.0	2.20	0.00
Shampoo - on the towels	3.7	0.73	0.70
Toothpaste - on the towels	1.8	0.37	0.70
Polyethylene terephthalate = plastic + food packaging + food storage	12.6	2.51	0.00
Chewing gum	3.7	0.73	0.30
Duct tape + food packaging tape	5.5	1.09	0.00
Disinfectant wipes	2.0	0.40	0.70
Food - See Breakdown for details	149.3	29.86	0.81
Foil (includes both food packaging and storage foil)	21.9	4.39	
Polypropylene	23.2	4.64	
Polyethylene (PE)	61.1	12.23	0.00
Nylon	21.9	4.37	
Silicone	2.8	0.56	
Salt - sodium chloride on Tshirt	9.0	1.80	0.00
totals	500	100.00	

Table 2. Food component of the trash simulant for testing

Item	gm in 500 gm trash batch	percent of food	approx. water content fraction
Sausage patty	8.34	5.60	0.7
Dried apricots	3.89	2.61	0.5
Scrambled eggs	7.78	5.22	0.8
Orange-pine drink	16.87	11.32	1
Apple cider	16.68	11.20	1
Pineapple drink	17.18	11.53	1
Frankfurter	7.96	5.35	0.8
Mac & cheese	9.91	6.65	0.7
Tortilla (all)	9.66	6.48	0.6
Peaches	8.90	5.98	0.75
Macadamia nuts	5.64	3.79	0.4
Sweet/sour chicken	15.68	10.52	0.8
Rice w/butter	8.90	5.98	0.8
Creamed spinach	4.83	3.24	0.8
Strawberries	0.56	0.38	0.9
Vanilla pudding	6.21	4.17	0.8
total	149.00	100.00	

III.   Mission Utility

A. Overall Utility Discussion

On Shuttle the trash was hand compacted into football shaped bundles, wrapped with duct tape to prevent spring back, stored in the Volume F compartment (that was vented to space), and returned to earth. On station the trash is hand compacted, temporarily stored in the habitat, transferred to the resupply vehicle such as the Russian Progress vehicle, and typically incinerated in the earth's atmosphere as the supply vehicle burns up upon reentry. The Shuttle method does not work for long duration missions because it is too expensive to provide large waste storage lockers that vent valuable air for long periods of time. The Station method does not work either because there are not likely to be resupply vehicles for long duration missions and overboard dumping also has problems as discussed below. Besides providing a replacement solution for trash management, the HMC has additional utility.

The utility of the HMC for future missions is comprised of the beneficial functions that it performs. The HMC reduces the volume of the waste, it disinfects/sterilizes the trash and thereby biologically stabilizes it, it recovers water for recycle, it produces tiles that can be used for augmentation of radiation shielding, and due to its microbial control reduces the microbial footprint in support of planetary protection requirements. Figure 9 illustrates these functions. This figure shows the trash input with its microbial burden and shows the products including disinfected reduced volume tiles, water, and radiation shielding. The rest of this section explores these beneficial functions in more detail.

B. Volume Reduction

Volume reduction is valuable because of the limited amount of volume available in the crew habitat. The food and supplies start out in the habitat and are used by the crew in the habitat. That means the trash is in the habitat. The trash is wet and contaminated with microorganisms. It is also the nature of packaged materials to expand in volume from the dense stored resources to the used condition. As can be seen in the upper left corner of Figure 9, the current method of reducing volume is the crew time intensive method of hand and foot compaction.
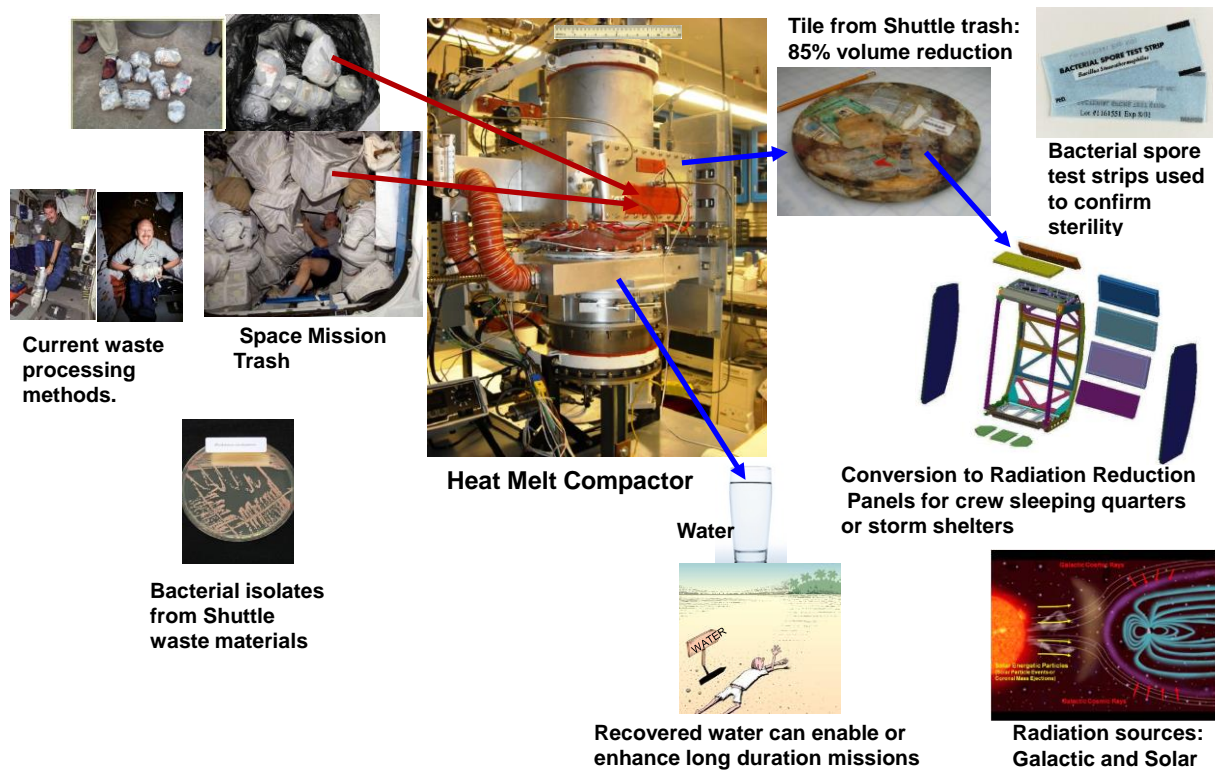
Figure 9. Beneficial functions of the HMC

The volume saved by mechanical compaction devices such as the HMC depends on the initial and final densities of the trash. The initial density of trash depends on the nature of the trash, the effort expended during the initial manual compactio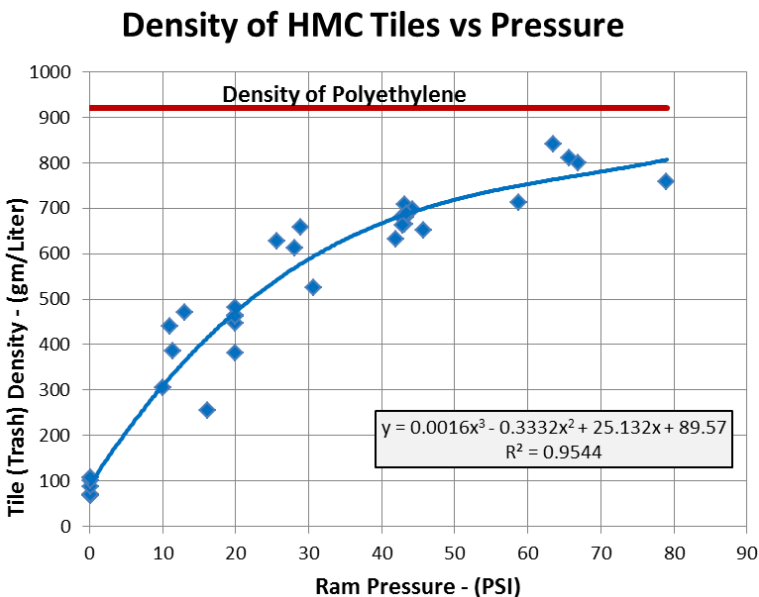n, and the configuration of the manually compacted material. The bulk density of hand compacted space mission trash varies considerably from roughly 70 kg/m^3 to 120 kg/m^3. The final density is dependent upon the pressure used to compress the trash, the configuration of the final product (affects bulk density), and the amount of spring back after compaction. Figure 10 shows the density of HMC tiles as function of ram compaction pressure. No single experimental campaign was conducted to specifically address the change of density with pressure in an HMC. The data points on the graph are from various heat melt compactor prototypes with trash compositions that varied somewhat, but were similar to the composition of the trash in the simulant described above. The runs include data from runs with temperatures from 150 C to 180 C. A few of the data points are from runs

Figure 10. Density of Tiles as a Function of Compaction Pressure

$$y = 0.0016x^3 - 0.3332x^2 + 25.132x + 89.57$$
$$R^2 = 0.9544$$

with some minor pretreatment of the trash such as cutting up the cloth and plastic or prepositioning the trash inside the compaction chamber. This accounts for some of the variation in the data. However, real applications of the HMC would involve use with trash batches that vary from use to use, so there will be similar and likely greater variation in actual applications of the HMC. The general trend is clear and reasonable. The tile density climbs fairly rapidly with pressure at the low pressures. All of the materials in the trash have a maximum solid density so that eventually the density will asymptotically approach a maximum density representing the average maximum density of all the components of the trash. The trash is mostly hydrocarbons including a large amount of plastic so the density of polyethylene is shown on the graph as a guide for what maximum density might be approached asymptotically as pressure goes to infinity. A relatively high density without requiring excessive pressure is desired and 50 psi (345 kPa) has been so far chosen as the pressure that produces reasonably high density without the diminishing returns that going to higher pressure would produce. At 50 psi (345 kPa) the volume of the trash will be reduced by 70% to 90%.

C. Microbial Control

If trash did not have microbes on it, it would not show microbial growth. Unfortunately space mission trash has been found to contain significant microbial populations, even pathogenic populations. Studies have been conducted to evaluate the microbial populations on space mission trash by looking at trash that was produced on Shuttle.[25-27] Table 3 shows a listing of bacteria that were identified on trash from several Shuttle flights. Table 4 shows yeasts and molds that were identified on Shuttle trash.

Table 3. Bacteria Identified in Shuttle Trash[26]

Trash source	STS 129	STS 130	STS 131	STS 132
Personal hygiene wastes	*Staphylococcus aureus,* *Bacillus subtilis ss subtilis, Staphylococcus sp* *Enterobacteraerogenes*	*Enterococcus pseudoavium*	*Staphylococcus aureus* *Staphylococcus epidermidis Bacillus subtilis ss subtilis*	*Curtobacteriumspp Sphingomonassanquinis* *Enterobacterpyrinus*
Food wastes	*Bacillus spp.*	*Enterococcus pseudoavium*	*Staphylococcus aureus* *Staphylococcus saprophyticus*	*Bacillus pumilus Sphingomonassanquinis*
Drink pouches	*Bacillus subtilis ss subtilis*	*Enterococcus pseudoavium* *Burkholderiacepacia*	*Staphylococcus aureus*	*Enterobacterpyrinus Citrobacterspp Sphingomonassanquinis* *Burkholderiamultivorans* *Enterobacterpyrinus*
External trash bag surfaces	*Bacillus amyloliquifaciens Bacillus pumilus*	*Microbacteriummarytipicum Bacillus amyloliquifaciens*	*Paenibacilluspabuli*	*Bacillus amyloliquifaciens* *Burkholderiapyrrocinia*
Internal trash bag surfaces	*Bacillus subtilis ss subtilis*	Isolates were not identified	*Bacillus subtilis ss subtilis,*	Isolates were not identified
MAGS/elbow pack contents	*E. coli,* *Citrobactermurliniae*	No sample	No sample	*Shigellaflexneri*

Opportunistic pathogens (red) isolated in all waste types.

Table 4. Yeast and Molds on Shuttle trash [25, 26]

Sample	Isolates-yeasts and molds
Drink pouches	Rhodotorula glutinis, Torulospora glutosa
Food	2 by microseq
personal hygiene	Candida albicans, Cryptococcus laurentii, Rhodotorula mucilaginosa
Internal Vol. F swab	Rhodotorula mucilaginosa
Exterior Vol. F trash football	Rhodotorula mucilaginosa
Interior Elbow Pack	1 by microseq

microseq: molecular ID methodology using an ABI3130 gene analyzer

Microbial control of the processed trash is achieved by heating the trash high enough to kill microorganisms and by drying the trash to prevent regrowth of microorganisms. In order to drive off the water from the trash, melt the plastic, and sterilize the trash, the HMC must heat the trash to a sufficiently high temperature and then hold it there for a while. To melt at least the polyethylene plastic the trash requires at least about 130 C. This temperature is sufficient to drive off the water at atmospheric or lower pressure. To sterilize the trash requires either dry heat or wet heat conditions. To sterilize any material, such as is done in autoclaves, the material must be held at a high enough temperature to kill microorganisms and spores for a specific amount of time. The higher the temperature the shorter the hold time needed. Dry heat sterilization requires longer hold times at a given temperature then wet heat sterilization (wet heat means with steam). It is not possible to assure that all areas of the trash will see steam during the processing so dry heat sterilization is assumed. At 150 C it takes about 3 hours at temperature to dry heat sterilize, and at 180 C it takes about one hour to dry heat sterilize.

Driving the water off makes the condensed water available for recycle and it dries the trash. Dry trash is important because trash that is dry enough does not support growth of microorganisms. It is well known that microbes do not grow on substances that would otherwise be food if the material is at a water activity of less than about 0.6. Water activity or a_w is the partial vapor pressure of water in a substance divided by the standard state partial vapor pressure of water. In the field of food science the standard state is most often defined as the partial vapor pressure of pure water at the same temperature. This means, for instance, that food that is dry enough to be in equilibrium with air at 60% humidity or below at 20 C will not support microbial growth. In climates with humidity that is regularly 80% or above, food left out never dries enough to stop microbial growth.

At a technical interchange meeting (TIM) – 2016 Trash TIM and HMC Stakeholder Meeting - held at JSC on 3/24/2016, NASA microbiologists presented and discussed the results of some the previous studies of Shuttle trash. The following quote from a 2012 ICES paper[21] seems to capture the consensus of the microbiologists:

> "STS trash wastes have an abundance of easily biodegraded compounds that can support the growth of microorganisms. The research presented here shows that large numbers of bacteria and fungi have taken advantage of this readily available nutrient source to proliferate. Exterior and interior surfaces of plastic film bags containing trash were sampled and counts of cultivatable microbes were generally low and mostly occurred on trash bundles within the exterior trash bags – Volume F compartment and additional waste containing zip-lock bags. Personal hygiene wastes, drink containers and food wastes and packaging all contained high levels of mostly aerobic heterotrophic bacteria and lower levels of yeasts and molds. Isolates from plate count media were obtained and identified and proved to mostly be aerobic heterotrophs with some facultative anaerobes. These are usually considered common environmental isolates on Earth. However, several pathogens were also isolated: Staphylococcus aureus and Escherichia coli. If storage of space-generated trash / wastes is the only 'treatment' option, then, to prevent crew exposure to dangerous levels of cross-contaminating pathogens, we recommend that food wastes be placed immediately into storage and the containers immediately sealed. We believe that a better treatment option would be to limit microbial growth through immediate dehydration of food, or other, wastes or immediate sterilization of these wastes. The results reported here can be used to determine requirements and criteria for NASA Waste Management System. These methods and resulting data will provide a basis for testing technologies for the ability to limit contaminant survival, growth and proliferation."

The HMC is a technology that clearly has the ability to limit microbial contaminant survival, growth and proliferation. An experimental effort was conducted to determine the ability of the HMC to sterilize the trash and to determine the conditions under which the HMC was most effective at sterilizing the trash. The HMC was operated at several different temperatures and different hold times at those temperatures. More than one method of evaluating the effectiveness of sterilization was used. The effectiveness was determined using autoclave spore strips, intentional injection of microorganisms, and analysis of the resulting HMC tiles for the presence of microorganisms. Generally it was found that at temperatures less than about 130 C or for hold times at temperature that were less than dry heat sterilization hold time, sterilization was not achieved.[38] However, for 150 C and 180 C runs with hold times at temperature of 3 hours and 2 hours respectively, sterilization appeared to be achieved. Figure 11 shows the

commercial spore strips and microbe inserted into the trash before the HMC processing. Tables 5 and 6 show the results for the runs at the conditions (high enough temperature and long enough hold time) that were effective at eliminating microorganisms in the trash. A temperature of 150 C and 3 hour hold time showed the best effectiveness (no evidence of viable microorganisms).
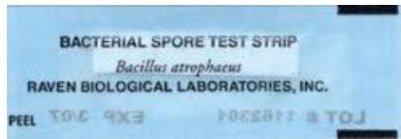

- *Bacillus amyloliquifaciens*

- *Rhodotorula mucilaginosa*

Autoclave Sterilization Bio Test Strips

BACTERIAL SPORE TEST STRIP
Bacillus atrophaeus
RAVEN BIOLOGICAL LABORATORIES, INC.
PEEL   LOT #: 1182504   EXP: 3/07

Bacillus atrophaeus is for dry sterilization;
Geobacillus is for steam sterilization

Figure 11. Test microbes and autoclave test strips inserted into waste for evaluating HMC effectiveness at

After the trash is free of microorganisms, there are still microbial concerns. The tiles contain hydrocarbons that are food for microorganisms, and if the tiles contain water and contain even a few microorganisms or are exposed to more microorganisms, then regrowth can occur. The tiles need to be dried to a_w less than 0.6.

During the heat up of the tiles, the water escapes from the tiles as soon as the temperature is above the boiling point. Until all of the free water in the trash is gone, the temperature of the trash wherever the free water is present in the batch will not rise above the boiling point at the local pressure. Free water means the water that is free to escape from the trash and is not contained by blocked spaces in the trash or by containers such as juice drink containers. Once the free water is gone, the temperature of the compressed trash begins to rise. Any contained water will heat up and begin to pressurize within its local containment to the vapor pressure of water at that temperature. This local pressurization within the compressed trash will tend to make steam and expand the containment that is keeping the steam from escaping. In addition, plastic containers such as the drink bags will eventually melt. Generally the expansion and the plastic melting eventually results in the escape of the remaining water.

Table 5. Microbial Analysis for HMC tiles processed at 180 C.

Sample HMC Disk #	9M	10 M	11 M
Core samples showing microbial growth	0/10	1/10	1/10
Commercial Spore Strips	Negative	Negative	Negative
R. mucilaginosa recovery	None	None	None
B. amyloliquifaciens recovery	None	None	None
Sterilizationtime (h:min)	1:59	1:09	2:07

Negative means that there were no living spores detected implying that all the spores had lost their viability (i.e. were killed). 1/10 means 1 of 10 core samples showed unidentified microbial growth.

Table 6. Microbial Analysis for HMC tiles processed at 150 C, 3 hrs.

Sample HMC Disk #	13M	14M	15M
Core samples showing microbial growth	0/10	0/10	0/10
B. atrophaeus (Top)	Negative	Negative	Negative
G.stearothermophilis (Top)	Negative	Negative	Negative
B. atrophaeus (Middle)	Negative	Negative	Negative
G. stearothermophilis (Middle)	Negative	Negative	Negative
B. atrophaeus (Bottom)	Negative	Negative	Negative
G. stearothermophilis (Bottom)	Negative	Negative	Negative
R. mucilaginosa recovery	None	None	None
B. Amyloliquifaciens recovery	None	None	None

Negative means that there were no living spores detected implying that all the Spores had lost their viability (i.e. were killed). 0/10 means 0 of 10 core samples showed unidentified microbial growth.

The expansion of trapped water has been observed on some HMC runs as the 50 psi (345 kPa) pneumatic piston was temporarily pushed backwards. It has been theorized that the push back was due to trapped water in a drink bag and eventual cessation of push back was due to melting of the drink bag and release of the water. It is possible that small amounts of water in confined areas remain in the tile after processing. This can happen because the force exerted by the high pressure of the steam in a localized area can be overwhelmed by the force exerted by the ram pressure over a much larger area. For instance a localized pocket of liquid water at 180 C with steam produced above it at 145 psi (1002 kPa) in a 1 cm square exerts 22.5 lb. (100 N) of force while the 50 psi (345 kPa) ram pressure exerted over the area of a 20.3 cm diameter circular ram exerts 7,270 lb. (32,340 N) of force. Water can be confined in the compressed trash due to localized features in the trash as well as due to plugging of the vents on the compaction chamber due to melted plastic or trash goo extruding into the vents. Avoiding plugging of the vents and the consequent blockage of water from escape is a primary reason for running the HMC processing chamber at about 1/5 of an atmosphere vapor pressure during heatup and ram compaction. The low pressure allows boil off of all the water at a boiling temperature (60 C) well below that when the plastic melts and plugging of the vents can occur.

Note that it is expected that the vents from the trash processing chamber will likely plug from extruded plastic and trash goo during every trash processing cycle. However, when the vent is the small passage between the edge of the ram and the wall of the containment vessel, the vent is reopened at the end of run and before the next batch as soon as the ram is moved at low temperature because the movement breaks the newly created seal between the ram edge and the wall. Other types of vents have to use other methods to deal with extrusion of liquid plastic and trash goo at high temperature processing conditions. The point of this discussion is that care must be taken in the form of temperature control and compaction pressure in order to avoid blockage of steam movement either due to local conditions in the batch or due to vent plugging and to remove all the water.

Inadequate water removal has been observed on some experiments because bubbles of confined water were observed inside the tile produced at the end of the experiment. An example of this is when the run was conducted with the steam boil off occurring at atmospheric pressure. At atmospheric pressure the batch must be raised to somewhat above 100 C, at which point plastic and goo are mobile enough in some cases to block vents and prevent full steam escape.

Some limited measurements of the dryness of the tiles produced in the HMC have been conducted. More experimentation and data are needed to confirm the conditions required to reliably remove enough water to produce 0.6 water activity throughout a product tile. It is clear, however, that if all the water is freed from containment in a batch and is allowed to escape at the high temperatures used for sterilization (typically 150 C), then the whole tile will be well below 0.6 water activity on the inside at normal room temperatures. Under such conditions the tile will not support regrowth of microorganisms on the inside after processing.

D. Water Removal and Recovery

Water removal is important both for recovery of water for recycle to the crew and for stabilization of the trash to prevent microbial growth. Water removal to a dryness level of 0.6 water activity was discussed above. There are two forms in which water leaves the trash batches during processing: squeezed out water and condensed steam.

Squeezed out water is an undesirable form of removed water. The water in the batch is in contact with food and miscellaneous trash and in some cases comes from unfinished drink pouches wherein the water is in the form of juice. Squeezed out water contains sugar, other dissolved and suspended hydrocarbons, and dissolved inorganics. These components in the water will tend to foul downstream (from the compactor) processing hardware such as the condensing heat exchanger, support microbial growth in the downstream hardware, and cause problems in hardware used to convert the water to potable conditions. It is a goal of the design and operation of the HMC to control and prevent squeezed out water.

It is expected that the condensed steam will be transferred to a mission water recovery system for processing to potable water. The existing water recovery system on Station consists of two main components – the urine processing assembly (UPA) and the water processing assembly (WPA). The UPA is a distillation system and the WPA contains contaminant adsorbents and a catalytic oxidizer (the volatile removal apparatus). Although one option is to put HMC water into the UPA, it would be simpler and more advantageous to add the HMC water to the system as feed to the WPA rather than as feed to the upstream UPA. Figure 12 shows diagrammatically how this might work.
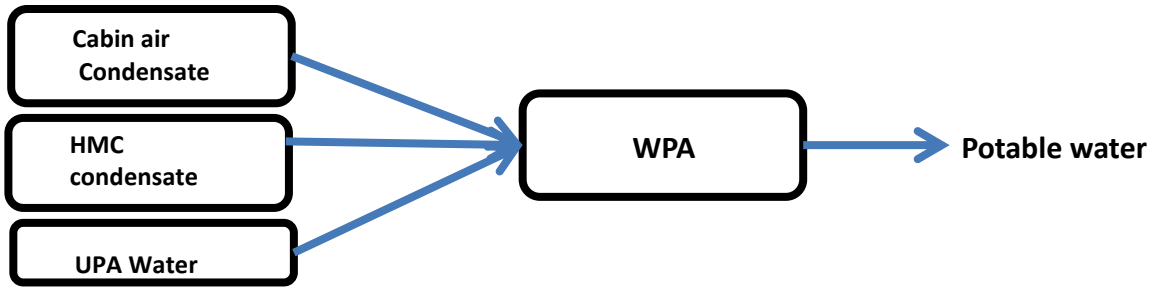
Figure 12. Integration of HMC condensate into water recovery system.

Most experiments on Gen1 and Gen2 have produced condensed steam, and this water has been analyzed. Average water composition of major constituents is shown in Table 7.

Table 7. Average composition of condensed HMC water

parameter	TOC	%TDS	pH	Na^+	NH_4^+	Cl^-	SO_4^{-2}	K^+	NO_2^-
ppm (except pH)	2200	0.03	3.5	4	22	10	4	2	3

The total organic carbon (TOC) is the major concern for processing in the WPA. The WPA is limited to 300 ppm feed,[8] and the HMC TOC is much higher than that. However dilution of the HMC water with UPA water and with cabin condensate, which together have much lower TOC and are a much larger flow stream than the HMC water production rate, results in a combined TOC feed to the WPA that is below the 300 ppm limit to the WPA. More testing is necessary to confirm the compatibility of the HMC with the water recovery system. A quote from a 2013 ICES paper summaries the use of HMC water:[8]

> *"TOC levels in water reclaimed by the HMC, in inoculated batches as well as non-inoculated batches, were relatively high compared to water that is normally treated by the WPA. Most of the contributors to HMC reclaimed water contain TOC, including fruit juice, food, shampoo, and wet disinfectant wipes. … The TOC levels found in HMC water preclude this water from being treated by the WPA, which cannot accept water with TOC exceeding 300 ppm. A potential solution is dilution of HMC product water with pre-existing UPA feed. Given a UPA feed rate of 4.28 L/CM-day with 150ppm TOC, and an HMC product water rate of 0.3 L/CM-day with 2200 ppm TOC (based on calculations and data presented in this paper), the combined feed to the UPA distillation assembly would be 4.58 L/CM-day with 284 ppm TOC. As the UPA feed has a higher volume and lower TOC than HMC product water, combining the two streams would yield a TOC low enough to feed into the WPA. Alternatively, HMC product water could be useful in non-potable applications. One possibility is the fabrication of a water wall for radiation shielding. Another possibility is using HMC product water in an untreated or semi-treated state for pre-existing water applications that do not necessitate potable water, such as flush water. Water has historically been considered very valuable in space, thus the incompatibility of HMC product water with the WPA does not decrease the value of the HMC's ability to recover water that would otherwise be wasted."[8]*

Conservatively assuming that the trash is only about 20% water, that the trash is 1.2 kg/CM-day,[34] and that the daily water needed for drinking and food prep is 2380 ml/crewmember-day,[39] then the HMC can recover about 10% of the water needs for the crew. This is a valuable contribution to the overall water balance.

E. Augmentation of Radiation Shielding

The radiation environment in space is significantly different from that on earth. The radiation in space consists primarily of high-energy charged particles, such as protons, alpha and heavier particles. Galactic cosmic radiation (GCR) and solar particle events (SPE) are the two main radiation sources of concern to astronauts. In interplanetary space the crew exposures will routinely exceed the exposures of terrestrial radiation workers.[28]

A 2014 publication describes the interplanetary environment well:

> "Most of the energetic particles found in interplanetary space are from the solar wind, which produces a constant flux of low linear energy transfer (LET) radiation. For missions outside of low Earth orbit, galactic cosmic radiation (GCR) will contribute a significant portion of the radiation dose accumulated by astronaut crew members. GCR ions originate from outside our solar system and contain mostly highly energetic protons and alpha particles, with a small component of high charge and energy (HZE) nuclei moving at relativistic speeds and energies. In addition to GCR, unpredictable and intermittent solar particle events (SPEs) can produce large plasma clouds containing highly energetic protons and some heavy ions that may cause a rapid surge of radiation both outside and within a spacecraft."[29]

Radiation shielding is important to protect the crew from galactic and solar sources of radiation. Galactic rays are continuous, mostly at a relatively constant level, and hazardous due their long term effects but not immediately hazardous to life and function. Solar radiation varies considerably and is hazardous not only in the long term, but can be life threatening in the short term when certain occasional solar events occur. A recent briefing to NASA's NAC HEOMD/SMD Joint Committee on April 7, 2015, provides current agency considerations regarding required radiation shielding requirements. According to this briefing "Good shielding … (20 g/cm2)" is considered adequate to provide reasonable protection to astronauts on a 900 day Mars Mission from health risks including cancer, acute radiation syndromes from SPEs, degenerative tissue effects, and central nervous system risks.[30]

As Figure 13 illustrates, it is found that generally the smaller the atomic mass of a material the better it is for space radiation shielding. Thus hydrogen is the best material for shielding in space. Unfortunately, liquid hydrogen needs to be kept too cold to fill the spacecraft walls, and gaseous hydrogen requires too much volume. Compounds that have a high molar ratio of hydrogen to other elements, that contain other elements with relatively low atomic masses, and that are liquid or solid (thus having higher densities) at ambient conditions are favored. Water and hydrocarbons such as polyethylene satisfy these requirements. Polyethylene has a molecular form of $(CH_2)_n$ and consequently a ratio of 2 hydrogens to each carbon. Polyethylene (PE) is currently considered a standard for comparison of radiation materials. Table 8 shows direct comparisons of polyethylene to other materials that confirm its advantageous performance as a shielding material.[31]
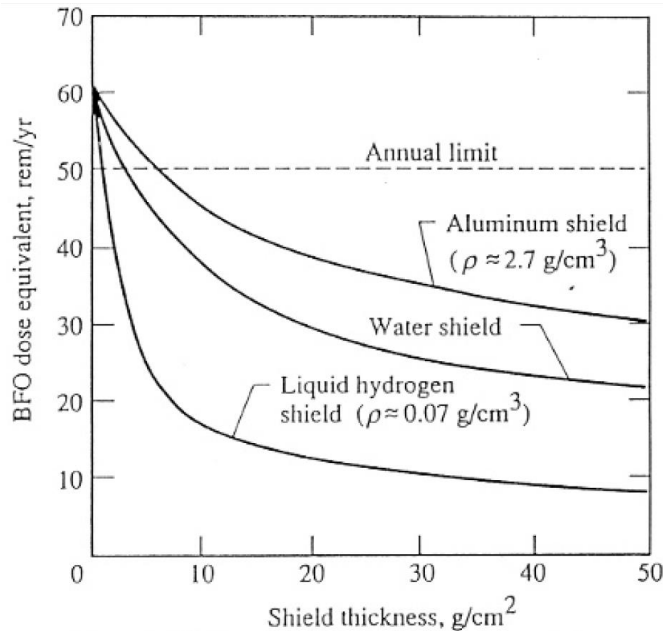

Figure 13. Shielding Effectiveness for GCR at Solar Minimum.[28] BFO = blood forming organs.

Table 8: Shielding mass needed to reduce Total Ionizing Dose to 1 cGy and 10 cGy during the July 2000 Solar Particle Event.[31]

Shield material	1cGy Band	10 cGy Band	1 cGy exp	10 cGy exp
Polyethylene	30 g/cm²	10 g/cm²	22 g/cm²	10 g/cm²
Carbon	37 g/cm²	12 g/cm²	25 g/cm²	12 g/cm²
Aluminum	40 g/cm²	13 g/cm²	29 g/cm²	13 g/cm²
Titanium	43 g/cm²	15 g/cm²	32 g/cm²	15 g/cm²

Note: cGy is a derived unit of ionizing radiation dose in the International System of Units (SI). It is defined as the absorption of one centi (1/100) joule of radiation energy per one kilogram of matter. Band and exp are forms of the solar particle event kinetic energy spectra.

Space mission trash contains a high percentage of hydrocarbons and is therefore mostly carbon and hydrogen on a molar basis. This can be seen from the list of ingredients of simulated trash shown in Table 1 above. A test of the effectiveness of HMC produced tiles for radiation shielding was conducted in 2015. The tiles were produced by the Gen1 HMC hardware using a trash model very similar to the one shown above in Table 1. The HMC tiles were found to be 90% as effective for radiation shielding compared to PE, the standard for comparison.[37]   More such tests are planned; however, it appears that HMC tiles made from space mission trash can be very effective at providing radiation protection.

At a Technical Interchange meeting held at JSC on March 22, 2016, JSC radiation protection experts discussed the use of HMC tiles for radiation shielding. One concept for radiation shielding is to use food, supplies, and HMC tiles for radiation shielding. In order to provide continuous radiation protection availability from the beginning of a mission, a portion of the spacecraft would have food and other supplies stored on the inside walls of the habitat. As

the food and supplies are consumed and converted to trash, the trash would be processed and returned to the walls to fill the shielding vacancies left by the used supplies. The concept is illustrated in figure 14.

Shielding depth is dependent upon the requirement for shielding and the density of the shielding material. According to recent source, good shielding is roughly 20 g/cm^2 of shielding material.[30] For pure water with a density of 1 g/cm^3 this means 20 cm of water on the wall. For polyethylene (PE) with a density of about 0.92 g/cm^3 this means a shielding depth of 21.7 cm. For HMC tiles with a density 0.7 g/cm3 and a shielding effectiveness of 0.9 compared to PE, this means a wall shielding depth of 31.7 cm. The Orbitec compactor and the current version of Gen2 HMC's scissor link ram operate with about 12 -15 psi (83-103 kPa) of compression force. Although intended to operate at 50 psi (345 kPa), Gen2 is currently limited to 12-15 psi (83-103 kPa) due a design error on the scissor link system. Some consideration has been given as whether this is adequate compression. As Figure 10 shows, 12 psi (83 kPa) pressure limits the HMC tile density to about 350 g/L density. Based on the 20 g/cm^2 for good shielding and the 0.9 effectiveness relative to PE, this would mean a wall thickness of 63.5 cm, which may be encroaching on the internal habitat volume. In addition, such low density means many large and likely connected air pockets inside a tile that could allow cabin air to enter the inside of a tile, bringing with it possible microbial contamination and moisture. Minimizing the thickness of HMC tile radiation shielding and minimizing the opportunity for microbial contamination of HMC tiles are two reasons for producing high density HMC tiles.
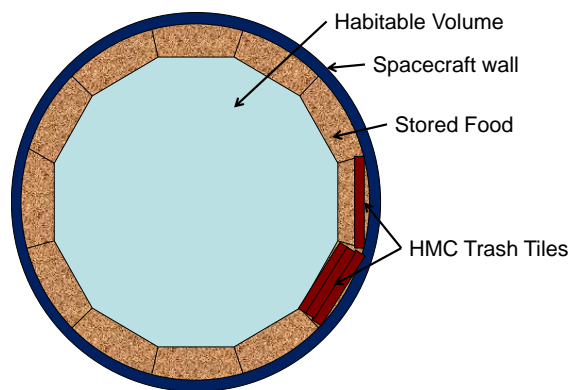

Figure 14. Concept for Using Food and HMC for Radiation Shielding.

F. Planetary Protection

An international treaty regarding treatment of celestial bodies was agreed to in 1967.[32] A 2015 ICES paper[33] discusses the treaty and NASA's current approaches to satisfying the treaty for missions such as a Mars mission:

"Subject to international treaty, the planetary protection obligations of spacefaring nations are described in the Outer Space Treaty of 1967 , where Article IX reads:

"...parties to the Treaty shall pursue studies of outer space including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose…

In November 2012, the NASA Advisory Council (NAC), an advisory group to NASA's senior leadership on challenges and solutions facing the agency, recommended the development of an implementing document for planetary protection requirements for future crewed exploration missions beyond Earth orbit. This recommendation sought to establish guidance on the application of COSPAR Principles and Guidelines for Human Missions to Mars for the teams developing future mission architectures and hardware. In March of 2013, NASA acknowledged the recommendation and established a multi - disciplinary team to create a set of planetary protection requirements for human missions which would parallel the existing NASA Procedural Requirement (NPR) 8020.12 Planetary Protection Provisions for Robotic Extraterrestrial Missions.

As the team deliberated, it was concluded that insufficient data were available on human exploration systems and their potential interactions with the Mars system environments (including Photos and Deimos) to construct effective, quantifiable requirements. This team instead created a NASA Policy Instruction (NPI) document…

While the NPI acknowledges the process for developing procedural requirements for human missions beyond Earth may take a few years, it provides insight into needed areas of scientific and technological study that can begin now. Three primary areas of focus are identified in the NPI: 1. Developing capabilities to comprehensively monitor the microbial communities associated with human systems and evaluate changes over time; 2. Developing technologies for minimizing/mitigating contamination release, including but not limited to closed - loop systems ; cleaning/re - cleaning capabilities; support systems that minimize contact of humans with the environment of Mars and other solar system destinations; 3. Understanding environmental processes on Mars and other solar system destinations that would contribute to transport and sterilization of organisms released by human activity.*"[33]*

The HMC is an example of a technology that can be developed for "minimizing/mitigating contamination release." By sterilizing and stabilizing the trash, the HMC clearly would minimize the biological footprint left on a planetary surface such as Mars. Consequently, another benefit of the HMC processing of trash is planetary protection.

G. Quantification of HMC utility

The HMC reduces the volume of the waste, disinfects/sterilizes the trash and thereby stabilizes it, recovers water, produces tiles for radiation shielding, and minimizes the microbial footprint for planetary protection. It is possible to quantify at least the benefits and costs of the HMC based on mass, volume, and power. Table 9 from a 2012 ICES paper summarizes these benefits. The base case represents recent trash estimates based on ISS and the maximum case presents a case with greater food waste and less contingency supplies left on the shelf at the end of the mission. It is expected that a flight unit would have a mass similar to the mass of the Gen2 unit; and since the mass of the water and radiation tiles alone are much higher than that, it is clear that the HMC more than pays for itself based on mass, power, and volume considerations alone.[34] The reduced crew hazard and improved planetary protection due to microbial control are added benefits that cannot be ignored, but which are not presently quantified.

Table 9. Benefits of Generation II Heat Melt Compactor for Two Cases (four-person, one-year missions)[34]

Trash Processing	Base case	Max. case
Mixed, wet trash to process	1215 kg	1942 kg
Water recovered from trash	229 kg	365 kg
Volume recovered by trash compaction compared to hand compacted trash	13 m^3	20 m^3
Volume of HMC generation II unit	0.14 m^3	0.14 m^3
Number of 0.23 m x 0.23 m radiation tiles produced	1060	1694
Mass of radiation shielding tiles produced	986 kg	1577 kg
Mass of HMC Gen2 unit	120 kg	120 kg
Energy required to process trash	2400 kWh	3900 kWh

IV. Consideration of Trash Processing Alternatives

A. Overboard Dumping

An obvious way of disposing of trash on space missions is simple overboard disposal. Unfortunately this method not only loses the resources that can be recovered from trash, but it is also not simple. An airlock and/or an ejection mechanism are some of the systems that would be necessary for overboard dumping. An airlock is necessary in order to get the waste to the vacuum of space without loss of cabin air. Once outside the trash is a navigation hazard because the trash will simply float along with the spacecraft; hence, an ejection mechanism is needed that moves the waste a far enough distance away in a desirable direction. A recent paper from the 7th Symposium on Space Resource Utilization explored the overboard disposal method for an Earth-moon L2 mission and summarized it as follows:

> "Over long-duration missions away from Earth, significant amounts of waste will be generated. Saving this waste to package and return to Earth or burn-up in orbit will no longer be an option and alternative solutions must be developed. One option that has been suggested is to dispose of the waste to space through a small airlock. An evaluation of physical reactions of the waste when exposed to a vacuum indicated that minimal water flashes to vapor upon initial exposure to the vacuum. Over time, approximately 20 percent of the total water in the waste will sublimate before the trash football is completely frozen. The initial hazard therefore of disposing of the waste to space is that these escaping volatiles can re-condense and contaminate the airlock surfaces or the airlock pump. Solid waste ejection using low velocity methods may be problematic for missions in a semi-stable orbit around the Earth-moon L2 point. While waste footballs released at select points in the orbit may intersect the lunar surface before having a chance to re-impact the spacecraft, the large number of waste footballs that will be generated indicate that another solution will be necessary. Several high-velocity disposal technologies were considered that were too large or too wasteful to recommend."[35]

B. Other Processing Technologies

Other trash processing technologies for long-duration missions have been considered in recent years. Each technology has its advantages and disadvantages. Every approach represents a region of multidimensional space with the dimensions being temperature, pressure, energy, composition (including addition of other substances such as oxygen), surface chemistry (use of catalysts), and micro-gravity operation. Key considerations after processing are whether there is overboard disposal (gas venting, liquid venting, solid ejection), whether microorganisms are controlled, and whether there is recovery of resources such as water. Overboard venting of gasified waste has the

advantages of removing biological hazard, recovering volume, and making the spacecraft lighter, which saves on fuel during mission velocity changes (delta v). As compared to other technologies HMC has the advantages discussed previously of microbial control, production of water and radiation shielding, volume recovery, and planetary protection. Ejection (easier for HMC tiles because they are already devolatilized) or venting of trash mass saves fuel needed for a delta v, but the ejection or venting means loss of HMC trash tiles that can provide radiation shielding. Some of the alternative trash processing technologies that have been considered:

- Pyrolysis produces a mixed gas of hydrocarbons, carbon monoxide, carbon dioxide, and a small amount of methane.
- Gasification and incineration produce mostly carbon dioxide, with smaller amounts of carbon monoxide, unreacted hydrocarbons, and trace amounts of methane.
- A catalytic reduction process directly produces about a 25% yield of methane from polyethylene. The remaining gases include carbon dioxide and carbon monoxide.
- A steam reformer can convert the waste into a gas mixture predominantly composed of carbon dioxide, carbon monoxide, and hydrogen.
- Ozone oxidation tests were performed with the prototypic waste and fecal simulants, and were shown to oxidize the waste to carbon dioxide.

An evaluation of these alternative technologies in 2014 selected steam reforming as the best alternative or complementary technology to HMC for further development[40] although constrained NASA resources have limited its development in recent years.

V. Requirements

The requirements for an HMC are derived from several areas. There are requirements needed to achieve the desired benefits, spacecraft integration requirements, chemistry related requirements, mechanical requirements, and safety requirements.

Requirements are typically written in statements that the hardware "shall" or "should" have certain characteristics. "Shall" statements mean that the hardware must have that characteristic, and "should" statements mean that it is desirable that the hardware have that characteristic, but it is not completely necessary. Requirements also have levels. The levels start with the most general requirements at level 0 and progress to successively more detailed requirements as the level number increases from 0 to 1 to 2 and so on. For the HMC the level 0 requirements with rationale are shown in Table 10. These requirements are almost the same as the requirements listed for a recent publically released NASA Request for Information (RFI) in February, 2016.[36] The desired utility for the HMC is contained in these requirements. Volume reduction is in L0.2; water recovery is in L0.3; radiation shielding is covered by L0.2 and L0.4; microbial stability is covered by L0.2, L0.3, and L0.4; and planetary protection is covered by L0.1, L0.2, L0.3, and L0.4. Current plans are to test an HMC prototype on ISS about 2019, so consequently there are requirements related to that – L0.5 and L0.6.

An example of Level 1 requirements is shown in Table 11. These have been somewhat reduced for this example, but it can be seen that the detail becomes higher and more specific as the requirement level goes up. For instance, while the level 0 requirement says how much water must be recovered, the level 1 requirement describes the quality of the water to be recovered.

Table 10. Level 0 requirements for an HMC

L0-RQMT ID	Requirement	Rationale / Comment
L0.1	The HMC shall be capable of accepting and processing mission non-hazardous trash per the trash model. The system shall be capable of scaleup to a system handling 4.4 kg/day of the trash in the attached trash model.	The waste model represents the mission nonhazardous waste that is expected to be put into the compaction system. For a space mission about 4.4 kg/day of trash is expected be generated from a 4 person crew.
L0.2	The HMC shall compact trash into a geometrically stable form (the residual) suitable for long term storage and application to spacecraft walls for radiation shielding. Final compacted density of the average trash that is detailed in the trash model attachment shall be 600 gm/liter or higher.	Compaction provides volume reduction which is a key HMC trash management benefit. About 80% or higher volume reduction is expected. The geometry is important - structural integrity can vary. The residual must not flake apart but it is not an item with specific structural properties.
L0.3	The HMC shall recover 90% or more of water from the compacted trash.	Water is a critical resource and the amount of water recoverable from trash can be significant.
L0.4	When removed from the HMC the residual shall be sterile. Under the range of humidity and other conditions that are reasonably likely to occur on a space mission, the residual shall be such that it will be biologically stable and inert for the length of a 3 year space mission.	For storage or placement on the walls of a space craft the residual must not support biological growth because this can be hazardous to crew health.
L0.5	The HMC shall be at a technology readiness level capable of a technology flight demonstration on International Space Station (ISS) by mid-calendar 2019.	ISS is the flight vehicle available for long duration microgravity testing.
L0.6	The test HMC shall be capable of 30 processing cycles on ISS.	The system is being tested on ISS, and 30 processing cycles is likely sufficient for a test. The processing cycles will not be back to back. They will likely be spread out over several months For deployment the system must eventually be capable of reliable operation for 2 to 3 years.
L0.7	The HMC shall be safe and conform to NASA safety requirements	Safety and safe operations of ground and spacebased systems is a high priority of NASA

VI.   Status of the HMC

The Gen2 hardware has been fully fabricated and assembled as is discussed in the background section above. It was built to satisfy level 0 through level 2 requirements. Testing of the Gen2 hardware so far has been very limited due to funding constraints. Future development on the Gen2 hardware includes increasing ram pressure and reducing system leaks as well as investigating its capabilities for avoiding plugging of the processing chamber vents, avoiding squeezed out water, producing good quality water, and producing vent gas that meets habitat air quality standards.

The current plan is for a flight test of an HMC on ISS by 2019. How and where this flight unit is fabricated and prepared for the flight test is in work.

Table 11. Somewhat simplified level 1 requirements for an HMC:

ID	Requirement	Level 0	Rationale / Comments
L1.1	**Accept and Process Non-hazardous Trash**	**L0.1**	
L1.1.1	The HMC shall process trash as defined in the description of average space mission trash as well as reasonable variation from the average. The HMC shall be able to process trash that contains 50% more or less of each listed component, trash with 10% or more meltable plastics, trash with up to 50% water, and trash containing twice the amount of food in the trash description.	L0.1	On actual space missions the individual batches of trash will vary somewhat from the average that is described in the attachment. The processing system must be able to handle a reasonable level of such variation. The 2nd sentence here describes some of the reasonable variation from the average case that needs to be accommodated.
L1.1.2	Trash shall be compacted in a single batch but may be loaded incrementally. The HMC should tolerate processing of additional trash on top of an existing tile.	L0.1	
L1.1.3	When the type of HMC being developed is scaled to process 4.4 kg of trash per day, it should be capable of fitting in a HMC volume approximately 19 in. x 23 in. x 33 in.	L0.1	Typical future missions plan for a 4 person crew producing about 1.1 kg of trash per person per day. Typical uncompacted trash density: 60 to 120 gm/liter. Volume for hardware is limited.
L1.1.4	The HMC should be capable of processing 1 to 3 batches per day.	L0.1	Multiple batches/day reduces HMC size but increases crew interaction and time.
L1.2	**Processed Trash, Geometrically Stable**	**L0.2**	
L1.2.1	Tiles should not release particles when subjected to handling by crew	L0.2	
L1.2.2	The HMC shall be capable of producing a tile such that tile dimensions of length, width or diameter shall not increase by more than 10% over a period of 30 days when exposed to the nominal ISS cabin environment.	L0.2	
L1.2.3	The processed tile shape shall allow storage in a single (full) cargo transfer bag (CTB) with a volumetric efficiency of 70% or higher. CTB internal dimensions are 19.5-in x 16.25-in x 9.5-in.	L0.2	70% volumetric efficiency means the volume is 70% solid residual at the desired density of 600 gm/liter with 30% void space between the pieces of residual.
L1.2.4	The HMC should produce square tiles 9 inches side length with thickness of from 0.5 inches to 6 inches -- 1 to 2 inches preferred.	L0.2	For use as radiation shielding the individual tiles must not be too thick in order to permit some layering to cover spaces between tiles. The 9 inch long squares fit in CTBs.
L1.3	**Water Recovery**	**L0.3**	
L1.3.1	The effluent water from the HMC should be capable of being processed by the ISS Water Recovery System. This means generally that the water should be less than about 5000 ppm of TOC and compatible with the existing distillation and/or multifiltration and catalytic oxidation process. This can be demonstrated on a ground system and does not need to be demonstrated on the flight system.	L0.3	Water from the trash processing system will be made potable by passing through the mission Water Recovery System. Some ways of collecting water from trash such as simple squeezing likely will produce water that has such high levels of organics such as sugars that the water would foul the ISS Water Recovery System and, therefore, would not be acceptable.
L1.3.2	The HMC shall provide for control of the released water consistent with ISS protocols. The HMC may vent water vapor and off gassing as limited by ISS operation protocols. ISS protocols include for instance that venting liquid water is prohibited, HMC pressure before vent <40 psi, temperature of vented gas 60-113F, dewpoint <60F, gases compatible with vent hardware, gases not reactive, no vented particles, and others. See the reference on the right in the comments section for a reference to a NASA vent requirements document.	L0.3	For details of requirements for vent to space vac on ISS: SSP 52000-IDD-ERP Rev H Sept. 2009. online at: http://www.biospaceexperiments.com/index_html_files/2009%20EXPRESS%20Rack%20Payload%20interface%20Definition%20Document.pdf section 5.4 Vacuum Exhaust, contains most of the relevant requirements.
L1.4	**Residual is Microbially Stable**	**L0.4**	
L1.4.1	The residual shall have a water activity level equal to or less than 0.6.	L0.4	Microbial growth on rad tiles on habitat walls can present a biological hazard to the crew. At water activity levels less than 0.6 the tile will not support microbial growth
L1.5	**Produce a Flight Demonstration unit by mid-calendar 2019**	**L0.5**	
L1.5.1	All parts of the HMC shall be ISS flight quality. This includes but is not limited to controls, electronics, materials, thermal characteristics, etc.	L0.5	
L1.5.2	The HMC shall be capable of operating in environments microgravity and 1 G.	L0.5	
L1.5.3	The HMC electrical power consumption should not exceed a peak power of 1000 Watts and should consume on average of less than 500 Watts.	L0.5	In addition to saving power, the ISS EXPRESS rack has limited cooling capacity. Keeping power consumption below these limits potentially allows air cooling. Higher power requiring liquid cooling is discouraged.
L1.6	**HMC Reliability / Maintainability**	**L0.6**	
L1.6.1	The flight test unit shall not require maintenance for the length of the demonstration test on ISS.	L0.6	
L1.7	**Safety**	**L0.7**	
L1.7.1	The HMC shall not release gases into cabin air that exceed the Spacecraft Maximum Acceptable Concentrations for Airborne Contaminants (SMAC) levels.	L0.7	Gases can be released to the cabin by intentional vent or by leaks. An online SMAC listing is: http://www.cdc.gov/niosh/docket/archive/pdfs/NIOSH-125/125-NASAJSC205841999.pdf More detail can be found in online publications at: http://www.nap.edu/search/?topic=293&term=smac

VII. Summary and Conclusion

Development of hardware for compaction of trash on space missions goes back at least as far as 1992 and STS 35. The development of a heat melt trash compactor began in 2003. The desire to eliminate hazards and to produce useful materials from trash has driven a development effort that since 2003 has produced several generational iterations of the HMC. The utility of the HMC is that it reduces trash volume, microbiologically stabilizes trash, recovers water, augments radiation shielding, and reduces the microbial footprint in support of planetary protection requirements. Overboard disposal and other methods of trash processing have been considered and to date have not been found superior to the HMC for most future long-duration missions. Achieving the functional benefits of the HMC results in requirements, which as they become more and more detailed, determine the design of the HMC hardware. Risk reduction testing of the HMC Gen2 hardware will help develop more detailed hardware requirements and better future prototypes. The next prototype is planned to be a unit for flight testing on ISS.

Acknowledgments

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