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Heat Melt Compactor Development Progress

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The status of the Heat Melt Compactor (HMC) development project is reported. HMC Generation 2 (Gen 2) has been assembled and initial testing has begun. A baseline mission use case for trash volume reduction, water recovery, trash sterilization, and the venting of effluent gases and water vapor to space has been conceptualized. A test campaign to reduce technical risks is underway. This risk reduction testing examines the many varied operating scenarios and conditions needed for processing trash during a space mission. The test results along with performance characterization of Gen 2 will be used to prescribe requirements and specifications for a future ISS flight Technology Demonstration. We report on the current status, technical risks, and initial Gen 2 test results. Also presented is an operational concept for an International Space Station vent-to-space Technology Demonstration.

Nomenclature

ConOps = Concept of Operations
ECLSS = Environmental Control and Life Support Systems
GCMS = Gas Chromatography Mass Spectrometry
Gen 1 = Generation 1 Heat Melt Compactor
Gen 2 = Generation 2 Heat Melt Compactor
HMC = Heat Melt Compactor
ISS = International Space Station
LSS = Life Support Systems
RFI = Request for Information
RFP = Request for Proposal
SMAC = Space Maximum Allowable Concentrations for Airborne Contaminants
SysML = Systems Modeling Language
TD = Technology Demonstration
TOC = Total Organic Carbon
TRL = Technology Readiness Level
VES = Vent Exhaust System

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I. Introduction

A previous report in July of 2014 described the development progress of the Gen 2 Heat Melt Compactor.[1] The Gen 2 unit is designed to be a flight-like, ground based engineering prototype with specifications that are applicable for an International Space Station (ISS) technology demonstration in a double locker EXPRESS Rack. Gen 2 has several major components for a systems level test at TRL 5[*] and is to examine four primary objectives for processing astronaut space trash: compaction; sterilization; recovery of water; and oxidative post processing of the effluent gases. Unfortunately the initial test and verification of Gen 2 was problematic due to difficulties with the compaction mechanism. This, in addition to funding constraints, resulted in only limited testing. Subsequently, the project's focused turned to examining ISS flight requirements in order to identify a baseline Concept of Operations (ConOps) for a future ISS Technology Demonstration (TD). In early 2016 a Request for Information (RFI) was released[2] to determine the level of interest and the capabilities of industry and universities in providing a trash processing system for demonstration on ISS. The RFI was well received by the community with a number of high quality responses submitted. In addition to the RFI, a technical interchange meeting was held with participation from stakeholders in the areas of human factors, mission planners, medical, ECLSS air and water, safety, operations, and radiation shielding. More recently, an examination of ISS interface document definitions and an assessment of the current operational capability of the Gen 2 unit was conducted. Theses activities along with FY17 programmatic guidance has resulted in the current efforts that are intended to reduce technical risks and to identify requirements within the context of a defined concept of operations for a future flight demonstration.

II. HMC Gen 2 Status

The current hardware build of Gen 2 has not changed from that previously envisioned[3] and is the follow-on effort from Gen 1 HMC work.[4567] The HMC is to provide the necessary functions of compaction, water recovery, and oxidation of noxious effluent compounds into gases suitable for safe release into the crew cabin. Figure 1 diagrams the bench scale Gen 2 system showing the primary functional subsystems and relevant components for a "vent-to-cabin" operational scenario.

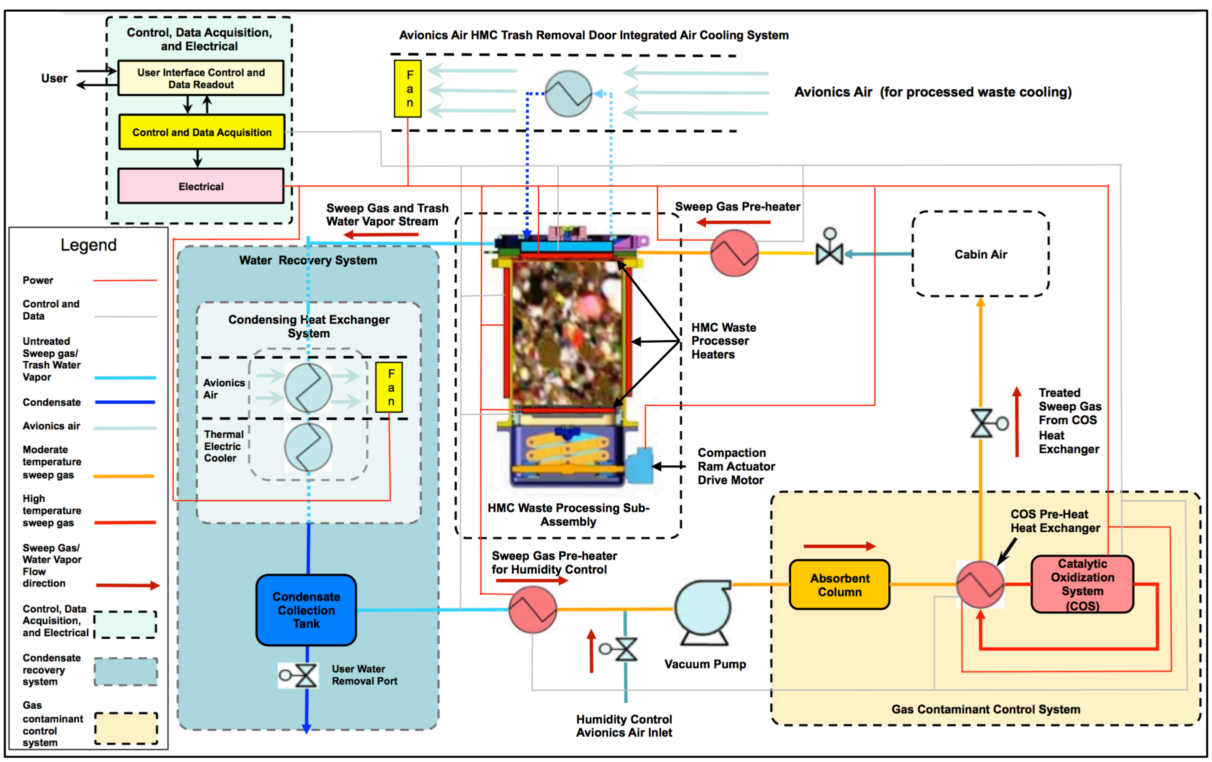


Figure 1. HMC Gen 2 diagram showing subsystems and components for trash compaction, water recovery, and oxidative processing of effluent gases.

[*] Per NASA Technology Readiness Levels, TRL 5 is system/subsystem/component validation in relevant environment.

The vent-to-cabin operation depicted by the system in Fig. 1 begins with treating the trash in the HMC Waste Processor with compaction and heat to boil-off the water. The water vapor is condensed and collected in the Water Recovery System. After the water is removed the trash stays under compaction and is further heated to sterilize and to melt the plastics contained in the trash. Throughout the heating process gaseous compounds evolve. These compounds are not condensable and so will flow through the condenser to the Gas Contaminant Controls System where they can be oxidized by the Catalytic Oxidation System. From there the oxidized gases, if sufficiently safe, can be released into the cabin. The system can be run near atmospheric or at sub-atmospheric conditions. Cabin air can be introduced as a sweep gas to dilute the effluent gases if needed. After the trash has been compacted and sterilized, avionics air is used to cool the system down so that the compacted trash can be removed at room temperature as a geometrically stable and biologically inactive tile.

Upon initial testing of the Gen 2 a difficulty was encountered with the compaction system having to do with the multi-link scissor mechanism/ball screw drive assembly.[†] The original design called for the ram compaction force to be 4000 lbs (50.6 psi) to compact a batch load of 500 grams of trash to produce tiles of dimensions 9 x 9 x 0.5 cubic inches (with rounded corners). Unfortunately, the actual ram force for the desired tile thickness was limited to 899 lbs (11.4 psi). In spite of this, several runs of trash processing that included compaction and water recovery were conducted. A summary of three compaction runs is shown in Table 1. Each run began with a 500 gram batch of trash comprised of components as listed in Appendix A. The initial un-compacted density of the trash batch was about 90 g/l. Gen 2 produced tiles with densities of 305 g/l, 386 g/l, and 470 g/l corresponding to the sequential runs from top to bottom in Table 1.

As expected increasing ram force produces higher density tiles. Shredding the trash and preferentially placing it in the compaction chamber also produces higher density tiles. The quality of Gen 2 tiles was such that for the lower 305 g/l density tile, there were visible voids and loose material on the surface, which could be of concern if water were absorbed on compacted foodstuff thus providing conditions for bacterial growth. Shredding and preferential placement was used to gain more uniformity in tile density and to reduce void volumes, particularly in the corners. However, for a true mission one would not necessarily require nor expect that the trash would be shredded or would be preferentially placed in the compactor. Figure 2 shows an image of the shredded trash before and after compaction.

Total organic carbon (TOC) was also measured for the collected water and had concentrations of ~2400 ppm.

Figure 3 plots the Gen 2 tile densities with Gen 1 densities as a function of ram pressure. Gen 2 tiles are seen to be comparable to and consistent with Gen 1 tiles. Figure 3 also shows that for shredding and preferential placement of the trash, the Gen 2 data have a steep slope over the 10-13 psi range of ram pressures tested.

During the runs other aspects of the compactor were found to be working as designed, including the system heating rates, heat and temperature limits necessary for boiling the water at atmospheric pressure, higher temperatures and hold time needed for melting the plastics and for sterilization, and uniform temperature distribution. The heaters are located on the exterior of the compaction chamber; hence insulating the core unit is necessary due to heat loss. Operation of the water recovery system indicated the thermal electric cooler and water condensation and collection system was effective. However, because the scope of testing was reduced, the catalytic oxidizing system was not tested.

Table 1. Summary of Gen 2 tiles that were produced.

Avg force at soak Temp, lbs	Avg Ram Pressure, psi	Avg Soak Temp, C	Run time, hrs	Initial wt, g	Density, kg/m^3	TOC in water, ppm	Description
798	10.1	148.8	5:41	490	305	-	Trash inserted as is, hand compressed
899	11.4	148.5	6:01	541	386	2461	Shredded trash preferentially placed in the compaction chamber to uniformly disperse and reduce air pockets to aid in making higher density tiles
1035	13.1	139.4	6:00	504	470	2342	Shredded trash preferentially placed in the compaction chamber similar to previous run except more focus on placing trash in corners. Torque assisted to achieve higher ram pressure.

[†] A design miscalculation resulted in reduced compaction forces.

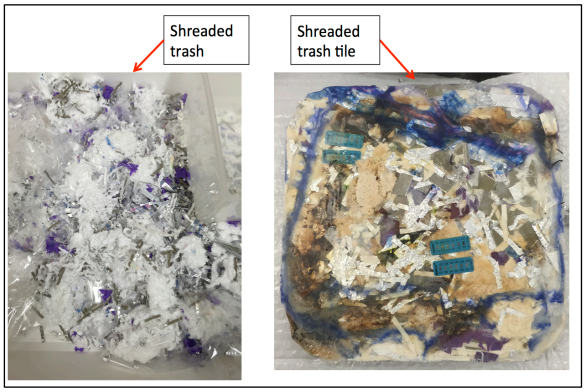


Figure 2. Shredded trash and resulting tile produced by Gen 2.

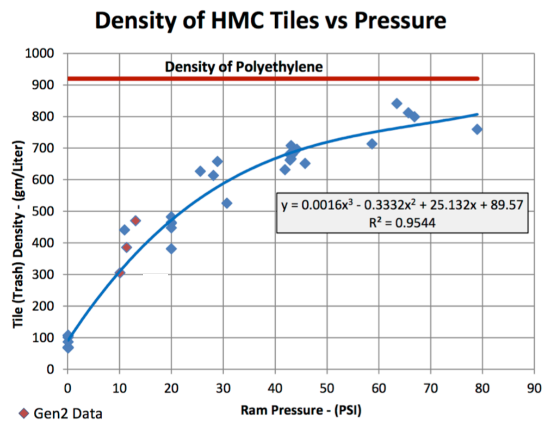


Figure 3. Compacted tile density vs. Ram Pressure for Gen 1 (blue) and Gen 2 (red).

The data in Table 1 were obtained with Gen 2 operating at one atmosphere. Gen 2 is also designed to operate at vacuum. Operating with vacuum allows for water to be removed at lower boiling temperatures. Lower temperature operation has the advantage of reducing the flow of foodstuff and dissolved sugars from being squeezed into and clogging vapor vent channels. Lower temperature also has the potential to produce cleaner recovered water because volatiles from solids are less likely to evolve.

For a vacuum to be sustained in the compaction chamber seals need to be leak tight particularly around the ram. Unfortunately for Gen 2 the sliding seal[‡] between the ram skirt and cylinder wall was not adequate for the desired vacuum; only ~13.7 psia was achieved in the compaction chamber. Figure 4 shows a damaged seal. Removal and examination of the ram seal showed that wear and scuffing due to friction against the cylinder wall and sliding across discontinuous surfaces caused the problem.

To achieve a better vacuum the original Teflon compression seal was replace and tested with various sized Viton O-rings. A suitable O-ring was found that allowed for ~7.5 psia in the compaction chamber. This equates to an additional ~592 lbs of force due to differential pressure across the ram. This, in combination with the force exerted by the mechanical linkage, results in ~1461 lbs (18.5 psia) that can applied to produce tiles of densities approximately 450 g/l as indicated in Fig. 3. Tests are currently being conducted with compaction chamber vacuum to determine whether tiles of good quality and higher density can be achieved.

Compacted trash tiles can be used as radiation shielding to augment radiation shelters. Higher density tiles would allow for more effective shielding by reducing the shelter shield volume while maintaining the same effective radiation protection.[3] Tiles produced from Gen 1 were tested for effectiveness in providing radiation shielding and the results indicated that the compacted tiles are 90% as effective in shielding from radiation when compared to the standard of high density polyethylene.[8]

Figure 4. Sliding seals can lead to wear and tear thus allowing gas and vacuum leaks around the ram skirt.

[‡] Original ram seals are graphite impregnated Teflon with an internal expansion spring, Parker Hannifin Corp.

III. ISS Vent Exhaust System Operation

The primary engineering functions expected of a trash processing system for long term human missions are: reduce trash volume; sterilize the trash; geometrically and biologically stabilize the trash; and recover resources (water and gases). An ISS technology demonstration would help validate trash processing technology in micro-gravity. An earlier working concept for an ISS flight demonstration was to have water and gas recovery handled with existing ISS life support systems. This would most likely require that the effluent gases and recovered water be pre-processed prior to being introduced to existing life support systems. For example, hydrocarbons released from the processed trash may require oxidation so as to satisfy requirements for Spacecraft Maximum Allowable Concentrations for Airborne Contaminants[9] (SMAC). Likewise, a water treatment subsystem may be needed to bring the TOC concentrations to an acceptable level. Technical solutions for these pre-processing systems are not well defined at this time. An evaluation and analysis would be needed to determine the constraints and requirements to integrate the HMC with existing ISS life support systems. Subsequently, one can ask the question, "Can a useful ISS technology demonstration be identified that reduces the need for integration with existing ECLSS?"

With this in mind, a series of discussions and meetings were held that resulted in a "vent-to-space" Concept of Operations (ConOps). The proposed ConOps makes use of the ISS Vent Exhaust System (VES) for directly venting effluents from the HMC to space. The advantages for the vent-to-space option are:

1. Venting to space can reduce or eliminate the need for water and gas pre-processing subsystems along with the associated maintenance, reliability, cost, safety, and integration requirements.
2. The VES provides a ready source of vacuum. Operating the HMC at vacuum allows for low temperature boiling or sublimation of water that has the benefit of recovering water with lower TOC concentrations than compared to higher temperature boiling at one atmosphere pressure. This is because volatile compounds resulting from the decomposition of solids (i.e., foodstuff, plastics) are less likely to evolve. Another advantage is that there is less chance of vent clogging due to the reduced ability of foodstuff to flow at lower temperature, particularly if the water is sublimated.
3. The VES would also allow for the possibility of venting all gases and water vapor directly to space thereby eliminating *any* need to interface with ISS water and air life support. However, it would be highly desirable to demonstrate water recovery as part of a technology demonstration, in particular, to verify that the technology to capture water will operate in micro-gravity.

To gauge commercial and university interest in a technology demonstration, a Request For Information[2] (RFI) was released in February 2016 with Level 0 and 1 preliminary requirements that are compatible with, though not necessarily restricted to, the vent-to-space ConOps. The requirements from the RFI are given in Appendix B.

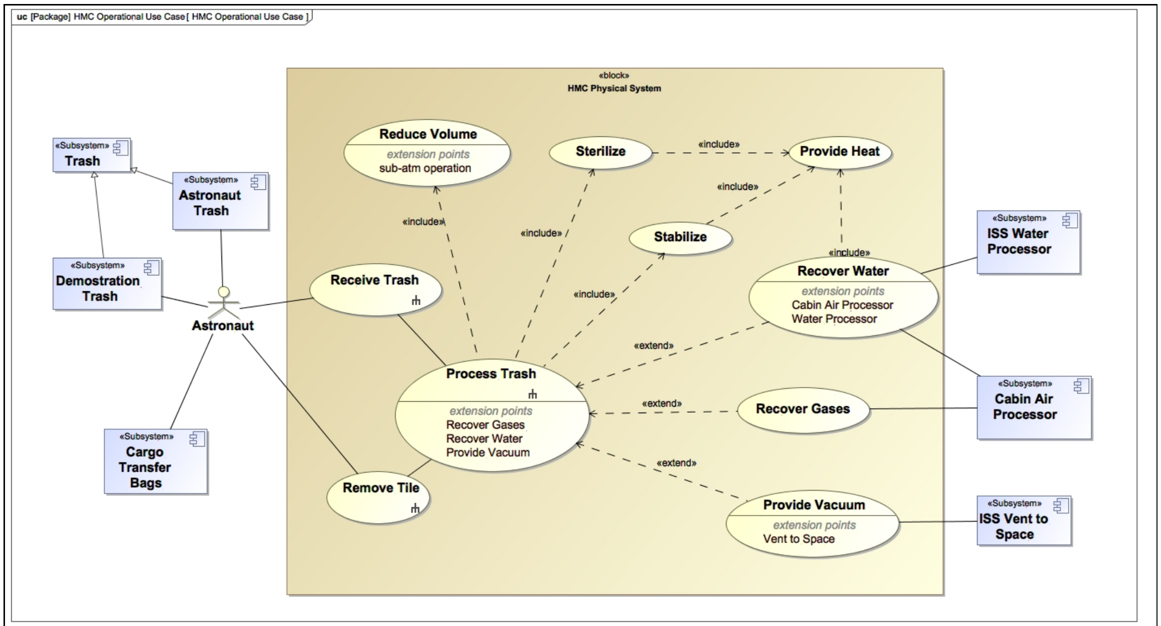
Figure 5 shows a use case diagram for the required trash processing system. The use case is described with Systems Modeling Language (SysML) and shows the internal dependencies between the various trash processing functions and the external interface dependencies with the ISS subsystems. A text description of the use case is also presented. The vent-to-space use case of Figure 5 is consistent with the requirements of the February 2016 RFI release.

IV. VES Venting Requirements

The ISS interface requirements for the VES can be found from the NASA SSP 57000-IDD, "Pressurized Payloads Interface Requirements Document, International Space Station Program"[10] and NASA SSP 52000-IDD, "EXpedite the Processing of Experiments to Space Station (EXPRESS) Rack Payloads Interface Definition Document." [11] Following is a summary of relevant interface requirements. For a complete description of the requirements refer to the aforementioned references.

A. Effluent gas dew point and temperature requirement

The primary requirement is not to allow any solids or liquids or the formation of such in the VES. The VES is a high vacuum venting system open directly to space. Venting of gases from an ISS experimental system is typically accomplished through throttling valves, and that any mass throttled from atmospheric pressure to vacuum can reach



HMC Concept of Operations for ISS technology flight demonstration for processing trash

1. Astronaut takes trash and inserts into HMC System
2. HMC receives trash.
3. HMC system processes trash. Trash processing involves:
   a. Reduce Volume to form a tile
   b. Sterilize (HMC approach is to use heat)
   c. Stabilize (HMC approach is to use heat to melt plastic – melted plastic cools to hold compressed trash as a geometrically stable tile; water activity less than 0.6 to inhibit biological activity)
   d. Recover Water (This is optional. HMC approach is to capture/condense water vapor from the heated trash or vent-to-space)
   e. Recover Gases (Catalytic oxidizer or if no gas recovery, vent-to-space)
   f. Provide vacuum (optional based on whether vent-to-cabin or vent-to-space)
4. Astronaut removes tile and inserts into Cargo Transfer Bag or other storage system.

Figure 5. Concept of Operations SysML use case diagram for HMC technology flight demonstration

very high velocities, hence, any solids or liquids that form in the vacuum vent from the throttled gases can potentially damage downstream sensors, instrumentation and control systems. To reduce this risk, NASA requires that any exhausted gas have a dew point of less than 15.6° C (60° F). Hot gasses can also be a risk to downstream components and so requirements specify that the temperature of any gas vented into the VES be less than 45° C (113° F). To visualize how these requirements can be met one can examine the Pressure-enthalpy phase diagram for water. To meet the requirements the state of the water vented can only be vapor and not more than 45° C. This ensures that the state of water does not cross into the two-phase region when throttling to a lower pressure at constant enthalpy (i.e., through a valve).

B. Mass flow requirement

Reference 7 Section 3.6.1.8 specifies the maximum acceptable flow rates into the VES. Maximum flow rate specifications are thresholds used to indicate possible cabin leaks into the experimental system. If maximum rates are exceeded the Rack Isolation Valve (RIV) will automatically close. The RIV is used to stop venting from an experimental system into the VES. The maximum acceptable mass flow rates are given in Table 2.

Table 2. Acceptable mass flow profile into VES to prevent the RIV from automatically closing [Ref 7 §3.6.1.8].

Time	Elapsed time	Pressure in VES	Acceptable Flow Rate at UIP
First 1 minute	0-60 seconds	666.6 Pa (5 torr)	3.081×10^{-1} kg/min (6.793×10^{-1} lbm/min)
Second 1 minute	60-120 seconds	66.66 Pa (500×10^{-3} torr)	5.320×10^{-3} kg/min (1.173×10^{-2} lbm/min)
Subsequent 5 minutes	120-420 seconds	10.67 Pa (80×10^{-3} torr)	1.658×10^{-4} kg/min (3.655×10^{-4} lbm/min)
Subsequent 15 minutes	420-1320 seconds	0.023 Pa (0.170×10^{-3} torr)	6.953×10^{-8} kg/min (1.533×10^{-7} lbm/min)

The HMC is expected to process 1.0 kg of trash containing up to 0.2 kg of recoverable water. The First 1 minute condition of Table 2 allows for up to 0.308 kg per minute of mass to be released over one minute. In this case, a subsystem to capture, store, and release the water would be needed. The water would need to be released into the VES *in a controlled fashion* so as to not violate the mass flow requirement as well as the dew point and temperature requirements. The VES can easily accommodate a 100L blowdown of air from atmospheric pressure. This is verified using a vent flow model [Ref 7, §3.6.1.8, Note 1]. By comparison for the HMC, 200ml of water is equivalent to 250L of water vapor. Verification of whether the VES can accommodate a 250L blowdown of water vapor will be needed.

For operational conditions without an intermediary subsystem to capture water, the water vapor will enter the VES directly from the HMC. Under this scenario the Second 1 minute constraint in Table 2 comes into play because it is highly improbable that all the water in the trash can be removed at a high enough rate and within the First 1 minute timeframe. The Second 1 minute requirement is highly restrictive when it comes to removing water during HMC processing with a maximum acceptable mass flow rate of 5.32 gram per minute over one minute. Tests conducted with the HMC have demonstrated water boil-off at an average rate of ~5 grams per minute during compaction. This would take 40 minutes to remove 200 ml of water from the trash, much longer than the First 1 minute allowance and clearly violating the Second 1 minute allowance. As such, an intermediary subsystem to capture and release the water would be necessary.

The above scenarios assume that the HMC can hold a tight vacuum so that only water vapor comes off the trash and so that there is no leakage of cabin air into the HMC system. However, from what has been learned from Gen 2, sliding seals will prove difficult in providing a reliable and consistent vacuum.

C. Gas component requirement

The VES can be subject to degradation if harmful and or corrosive gases are vented. A list of gas compounds that are approved for venting are given in Appendix D of NASA SSP-IDD 57000. Gases are generally not allowed if they condense on the surfaces of VES vent tube or on VES components. If they are condensable, then SSP-IDD 57000 states that, "Payloads venting to the ISS VES/WGS shall provide a means of removing gases that would adhere to the ISS VES/WGS tubing walls at a wall temperature of 4 °C (40 °F) and at a pressure of 10^{-3} torr." Measurement of effluent gases from Gen 1 tests with mixed component trash has identified the gases listed in Table 3. Gases evolving from individual trash components have recently been measured and are reported elsewhere.[12]

D. Contaminant control

Earlier operating scenarios called for the trash to be processed at near one atmosphere and that the effluent gases be processed with a catalytic oxidizer before safely releasing into the cabin. An alternate operating scenario envisions processing the trash under a vacuum. Vacuum processing allows water to boil or sublimate at lower temperatures in accordance with the saturated solid/liquid/vapor curve. Lower temperature operation has the potential for less contaminants in the collected water and in the effluent gases during water recovery. Figure 6 shows measured Total Organic Carbon (TOC) from a previously HMC Gen 1 experiment.[§] Processing at 80°C shows little TOCs being generated and that at temperatures at about 100 °C TOCs become apparent. A previous GCMS analysis[13] of Gen 1 gas composition has hinted at reduced production of organics at lower temperature relative to higher temperature processing. Low temperature water removal during trash processing could increase the cleanliness of recovered water and reduce gas contaminants. Low temperature boiling and sublimation is

[§] HMC Venting Telecon held on 9/14/14

routinely used in the food industry (lyophilization, freeze-drying) to remove water and to concentrate precipitates and solids while minimizing production of volatile compounds.

Table 3. Effluent gas concentrations as measured from HMC Gen 1 processing

Compound	Conc mg/m^3	Compound	Conc mg/m^3	Compound	Conc mg/m^3
Cmpd 51: 2-Furaldehyde	124.84	Cmpd 71: Dodecane	2.35	Cmpd 1: Formaldehyde	0.29
Cmpd 7: Acetone	33.47	Cmpd 58: Heptanal	1.95	Cmpd 65: Eucalyptol	0.23
Cmpd 37: 2,3-Pentanedione	31.04	Cmpd 9: Furan	1.88	Cmpd 36: 3-Pentanone	0.19
Cmpd 32: 2-Chloroethanol	26.05	Cmpd 3: Sulfur dioxide	1.82	Cmpd 34: 2-Pentanone	0.18
Cmpd 28: 3-methyl-Butanal	21.58	Cmpd 29: 3-methyl-2-Butanone	1.80	Cmpd 66: Limonene	0.17
Cmpd 69: Nonanal	18.72	Cmpd 67: Hexanoic Acid	1.43	Cmpd 63: Decane	0.16
Cmpd 31: 2-methyl-Butanal	14.08	Cmpd 2: Carbonyl Sulfide	1.41	Cmpd 18: 1-Propanol	0.15
Cmpd 8: Propanal	13.07	Cmpd 5: Methanol	1.33	Cmpd 40: 2,3-Dimethyfuran	0.13
Cmpd 61: 5-Methyfurfural	10.03	Cmpd 68: Undecane	1.21	Cmpd 26: Benzene	0.09
Cmpd 16: Carbon Disulfide	9.50	Cmpd 11: Formic Acid	1.21	Cmpd 41: Propyl acetate	0.07
Cmpd 17: 2-methyl-Propanal	9.50	Cmpd 35: Pentanal	1.19	Cmpd 13: Dimethyl Sulfide	0.07
Cmpd 19: Ethylene Sulfide	8.54	Cmpd 54: o-Zylene	1.18	Cmpd 74: Menthyl acetate	0.07
Cmpd 23: 2-Methylfuran	6.72	Cmpd 6: Ethanol	1.12	Cmpd 33: Heptane	0.04
Cmpd 50: 2-Methytetrahydrofuran-3-one	6.64	Cmpd 53: m/p-Zylene	0.89	Cmpd 25: 2-methyl-1,3-Dioxolane	0.04
Cmpd 30: Acetic Acid	5.97	Cmpd 56: Styrene	0.83	Cmpd 43: 2,3,3-Trimethylpentane	0.02
Cmpd 22: 2-Butanone	5.30	Cmpd 14: Acrylonitrile	0.80	Cmpd 24: 1,3-Dioxolane	0.02
Cmpd 64: Octanal	4.93	Cmpd 70: Menthone	0.61	Cmpd 42: 2,3,4-Trimethylpentane	0.02
Cmpd 4: Acetaldehyde	4.57	Cmpd 62: Pentanoic Acid	0.52	Cmpd 46: 1-Octene	0.02
Cmpd 12: 2-Propanol	4.44	Cmpd 10: Pentane	0.52	Cmpd 57: Nonane	0.02
Cmpd 60: Benzaldehyde	3.63	Cmpd 55: Butanic Acid	0.42	Cmpd 45: 2,2,5-Trimethylhexane	0.01
Cmpd 44: Propanoic Acid	3.61	Cmpd 38: 2,5-Dimethyfuran	0.37	Cmpd 49: trans-2-Octene	0.01
Cmpd 59: 2-Acetalfuran	3.43	Cmpd 20: Hexane	0.35	Cmpd 27: 4-methyl-1,3-Dioxolane	0.01
Cmpd 48: Hexanal	3.35	Cmpd 47: Octane	0.35	Cmpd 39: 2,4,4-Trimethyl-1-pentene	0.00
Cmpd 21: Butanal	3.16	Cmpd 73: Carvone	0.34	Cmpd 15: Methylene Chloride	0.00
Cmpd 72: Decanal	2.58	Cmpd 52: Ethylbenzene	0.32		

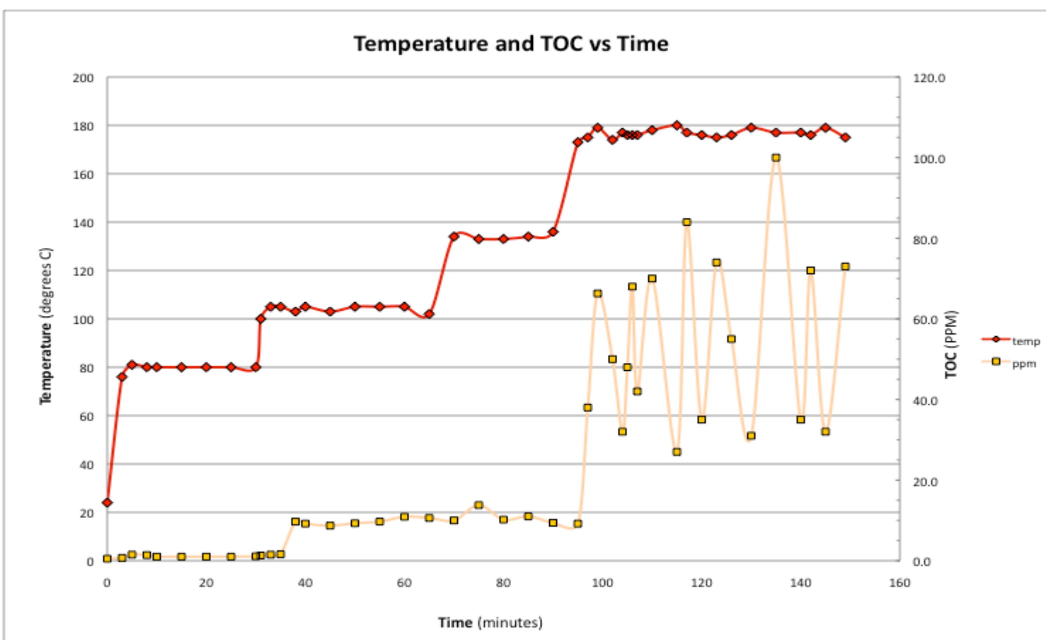


Figure 6. TOC concentration in effluent gas during HMC Gen 1 trash processing.

V. HMC Vent to Space Operational Approach

The ISS flight demonstration ConOps for HMC as shown in Fig. 5 shows the functional use cases and their dependencies both internally (within the HMC system block) and externally (outside the HMC System block, i.e., interface to the ISS Life Support Systems). Following SysML conventions, "include" dependencies (i.e., <<include>>) indicate that the use case at the tail end of the dashed line "uses" the use case at the head of the dashed line. For example, Process Trash includes (aka "uses") the use cases of Reduce Volume, Sterilize, and Stabilize. The "extend" dependencies (i.e., <<extend>>) displays the condition when the extending use case is used by the extended use case. For example, when Process Trash requires "Recover Water", then the Recover Water use case is used to extend the Process Trash functionality with water recovery. With this in mind, an HMC ISS flight demo that processes trash *shall* reduce volume, sterilize, and stabilize. Optionally, if water is to be recovered, then a recover water function is needed; likewise, with recover gases and provide vacuum. Though not explicitly indicated, there is an obvious requirement that any trash processing system needs to be safe.

Providing vacuum will depend on whether trash processing is done at sub-atmospheric or near atmospheric conditions. Sub-atmospheric operation will require a vacuum source and has the advantage of lower boiling temperatures when removing water that can result in recovering cleaner water with cleaner effluent gases. Lower temperatures during water recovery also have the possibility of reducing any dissolved and solid contaminants from being squeezed into and clogging vents. The vacuum source can come from the VES or from a vacuum pump. If vacuum is from the VES, the processing chamber of the HMC must be leak tight to prevent the RIV from being tripped. Sub-atmospheric conditions in the processing chamber also have the advantage of preventing any noxious gases from leaking into the cabin. One disadvantage resulting from a vacuum is the reduction of heat transfer in the compaction chamber that is needed for removing water and for plasticizing and sterilizing the trash. However, the applied mechanical force from the ram will increase thermal contact heat transfer between the tile surface and the heated wall of the compaction chamber as well as within the compacted trash tile itself.

Leak tight seals are necessary for sub-atmospheric operation and must be robust enough to operate with a one atmosphere pressure differential. Near atmospheric operation has a slight advantage over sub-atmospheric operation in that the seals need operate with a much smaller pressure differential. In both cases, however, seals should be able to handle off nominal pressure excursions (i.e., liquid flashing in the compaction chamber) or some other form of pressure relieve (i.e., pressure relief valve) should be provided.

Based on the above discussion and based on additional considerations that include the current state and operating capability of Gen 2 and the technical maturity of required subsystems, an operational concept for an HMC ISS flight demonstration was developed. Besides the required functions of volume reduction, sterilization, and stabilization, the following operational concept is intended to also recover water at low temperature using vacuum with venting of undesirable effluent gases to the VES during higher temperature plasticization and sterilization.

E. Operational Concept

Figure 7 diagrams a possible system layout and components for an HMC flight demonstration. The system is composed of the compactor, VES vacuum supply and venting, an adsorbent pump for water capture under vacuum, and a means for water release during adsorbent regeneration. The system provides for all the use case functions in Fig. 5 except for gas recovery.

The operational concepts corresponding to Fig. 5 have separate subsystems for low temperature water collection, adsorbent regeneration with water release, and high temperature processing to plasticize and sterilize the trash tile while releasing effluent gases to VES. Under this concept, the processes for clean water collection and dirty effluent gas handling are decoupled. This allows the HMC to first collect water, and then release it to the cabin (if it is clean enough to satisfy SMAC). During water release, the HMC processes the dry trash at higher temperatures and vents the effluent gases to the VES. The operation proceeds as follows:

1. Evacuate HMC compaction chamber and vent lines with vacuum from VES. This will be a blowdown of approximately 0.3 liter of air from one atmosphere to between 1 to 11 torr depending on desired pressure in compaction chamber. This should take less than one minute or the system is throttled accordingly to prevent vigorous boiling of any liquids that might expulse solids into HMC ram vents.
2. After achieving the desired vacuum, close off venting to the VES and use an adsorbent pump to pull water from the trash at low temperature of between of between 0 to 10° C corresponding to the vacuum pressure. Water vapor continuously adsorbs selectively to the adsorbent while maintaining vacuum. This approach eliminates the need for the VES to be continuously connected to the HMC system and so reduces any risk of cabin air loss due to vacuum seal failure. The conditions for water removal from the trash can either be

boiling or sublimation, depending on the vacuum pressure, applied heating power to the trash, and system heat leaks. Water should come off relatively clean and minimal volatiles are expected to off-gas at these low temperatures. Active cooling of the adsorption pump can be used to increase the rate of adsorption and to change the adsorption isotherm. Note that active cooling may be needed to remove heat of adsorption from the adsorption pump. If the rate of water removal needed is limited by the rate of adsorption then the VES may be used to assist, however, water will be lost.

3. After water is removed, disconnect adsorbent pump from HMC vent line and proceed with two parallel operations.
    1. Regenerate adsorbent by desorbing water with heat and cabin air. Release moist air to cabin and recover water using cabin air dehumidification systems. Hopefully the water released will be sufficiently clean so that no pre-processing is needed. This will need to be verified in the laboratory.
    2. In parallel, begin heating the HMC compaction chamber to plasticize and sterilize the trash. Vent effluent gases containing contaminants to the VES. Because the trash is now dry and most of the water is already removed, there shouldn't be any problems with meeting the VES mass flow or water vapor dew point requirements. There may be a need for a heat exchanger to cool the gas in order to meet temperature requirement. Depending on composition of the effluent gas, there may still be a need to examine the dew points of component gases. This will need to be examined with laboratory testing and analysis.

4. After trash compaction, sterilization, cooling, and tile removal, and after adsorbent regeneration, system is ready for new batch of trash.

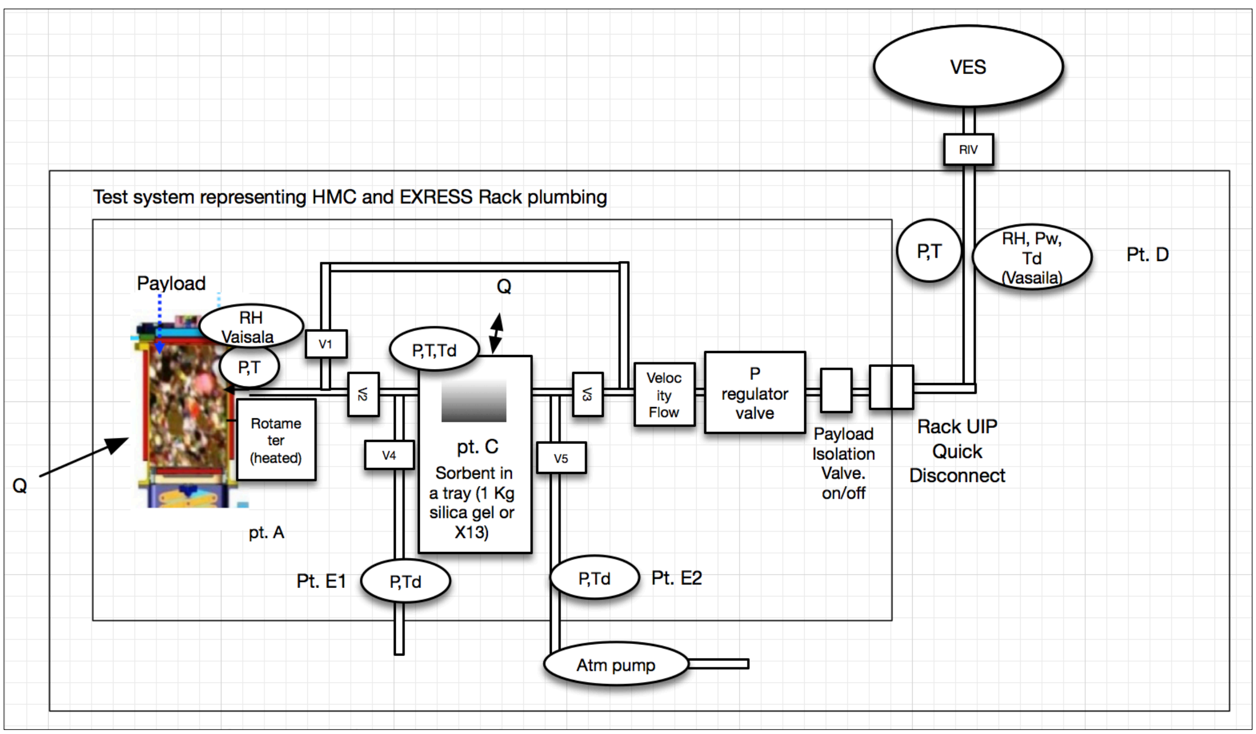


Figure 7. Test system flow schematic corresponding to HMC TD operational concept.

VI. Technical Risk Reduction

The HMC project is currently undergoing a risk reduction campaign to help with defining trash processing requirements that would be useful for guiding any future ISS technology demonstration Request for Proposal. A prioritized list of risks is shown in Table 4. Risk 1, which is to determine the contaminant off-gassing from individual trash components, is complete and the results having been documented.[12] Risks 2-6 are expected to be addressed at some level this year. Risks 7 and 8 are of lower priority. These risk are not all-inclusive, but represent those that are considered most important.

Table 4. Highest technical risks in priority order. There is a need to study and experimentally examine these risks to help define requirements for an RFP.

Risk Priority	Activity	Why is this needed for the RFP	Experimental risks/comments
1	Contaminant sources	Need to identify the composition of the waste model that respondents to RFP must satisfy.	Risk that testing of individual component testing is not representative of mixed waste behavior.
2	Pressure control and flow rates of the HMC system for vent to space.	Need to confirm that a pressure regulator will provide adequate HMC pressure control and meet the requirements for flow into the ISS vent system.	Requires leak tight system.
3	Sub-atmospheric vs. near atmospheric testing	Testing on Gen1 revealed that atmospheric operation can result in premature plugging of vents, inadequate water removal, and poorly formed tiles. More clarity is needed to determine how to write RFP requirements. Should the RFP require sub-atmospheric operation or simply require that the system reliably remove the water, melt plastic, and sterilize?	There is a need to identify candidate adsorbents to remove and store water from the processed trash. Though there exists abundant data on adsorption isotherms, testing will be needed to determine adsorption and desorption rates, and adsorbent robustness when exposed to liquid water, and other effects due to gas impurities.
4	Tile off gassing	Do RFP requirements need to include some special processing steps such as special bags for the trash and/or formed tiles that would limit off gassing?	Tiles may off gas differently depending on whether they were produced by near or sub-atmospheric processes.
5	Analysis of contaminants in HMC water	Flow rates and dew points are needed for all the components (water and others) that would go to the ISS vent system from the HMC.	Obtaining data to adequately cover the broad parameter space for different dissolved compounds in water and/or the water analysis may be too difficult or too expensive.
6	Flammability evaluation for evolved combustible gases	Need to understand the flammability issues and conditions associated with combustible gases that evolve from trash processing. Need to know how this constrains the RFP requirements for hardware design - seals, purging, maximum size of chambers, component pressure ratings, and sensors.	Subject matter expert needed.
7	Ability of ram to handle sudden waste chamber pressure rises.	Sudden pressure rises have been observed in previous pneumatic ram testing such that the ram was forced to retract. Need to evaluate whether scissor link system can also safely retract when necessary.	Damage to scissor link system due to slow response to pressurization. Current system leaks too much to evaluate pressure buildup. Failure of Gen 2 system components such as force sensor used for feedback control.
8	Gunk buildup	Gunk buildup limits the reliability of the HMC system. Knowledge of the gunk buildup can affect how this issue is captured in the RFP.	Risk that gunk builds up rapidly and forces premature rebuild of Gen 2. This risk may be mitigated by the development of specialized bags that retain trash and gunk while being permeable to water and water vapor.

VII. Summary

HMC Gen 2 is operational and can now be used as a platform for testing and verifying relevant trash processing subsystems. Near term use would be to test technologies proposed for a future ISS technology demonstration. Risk reduction activities are currently being conducted to identify requirements for a VES vent-to-space Concept of Operations. An operational concept for using adsorbent vacuum pumps to recover water from trash and for compatibility with ISS VES integration requirements are being examined and tested. Additional acquisition information may be provided in 2018 to support a flight demonstration in the 2021-22 time frame.

Appendix A

Waste Model used for Gen 2 tiles listed in Table 1.

HMC waste Mode l kg/cm-day	HMC Batch constituents	gm in 500 gm HMC batch	percent	water fraction assumptio n	water mass (grams)	Gen2 - 1" tile -929g (wt in g)
0.1733	cotton T shirt	**84.0**	16.83	0.06	5.04	156.07
0.0761	towels	**37.0**	7.41	0.06	2.22	68.75
0.0134	computer paper + food packaging paper	**6.2**	1.24	0.06	0.37	11.50
0.0000	none	**0.0**	0.00		0.00	0.00
0.0299	dry lab chem wipes	**14.0**	2.81	0.06	0.84	26.01
0.0598	Huggies	**29.0**	5.81	0.70	20.30	53.88
0.0235	nitrile gloves	**11.0**	2.20	0.00	0.00	20.44
0.0073	shampoo - on the towels	**3.7**	0.73	0.70	2.57	6.81
0.0037	toothpaste - on the towels	**1.8**	0.37	0.70	1.28	3.41
0.0260	PET = plastic PET + food packaging PET + food storage PET	**12.5**	2.51	0.00	0.00	23.31
0.0073	chewing gum	**3.7**	0.73	0.30	1.10	6.81
0.0109	duct tape + food packaging tape	**5.5**	1.09	0.00	0.00	10.14
0.0002	Velcro (none - too small)	**0.0**	0.00	0.00	0.00	0.00
0.0046	Disinfectnt wipes	**2.0**	0.40	0.70	1.40	3.72
0.3075	**See Food Breakdown on right**	**149.0**	29.86	0.81	120.69	276.84
0.0389	Foil	**18.9**	3.78	0.00	0.00	35.09
0.0477	PPE	**23.1**	4.64	0.00	0.00	43.00
0.1271	polyethylene	**61.0**	12.23	0.00	0.00	113.34
0.0450	Nylon	**21.8**	4.37	0.00	0.00	40.53
0.0058	Silicone	**2.8**	0.56	0.00	0.00	5.19
0.0064	Aluminum foil	**3.0**	0.60	0.00	0.00	5.57
0.0000	none	**0.0**	0.00	0.00	0.00	0.00
0.0180	salt - sodium chloride on Tshirt	**9.0**	1.80	0.00	0.00	16.72
				total water (grams)	155.81	
1.0324		**499.0**	100.00	percent water in waste	31.22%	

gm in 500 gm HMC batch	Item	Fract water	gm water	Gen2 - 1" tile -929 g (wt in g)
8.34	Sausage Patty	0.7	5.84	15.50
3.89	Dried Apricots	0.5	1.94	7.22
7.78	Scram.Eggs	0.8	6.22	14.45
16.87	Orange-Pine drink	1	16.87	31.34
				0.00
7.96	Frankfurter	0.8	6.37	14.80
9.91	Mac & Cheese	0.7	6.94	18.41
9.66	Tortilla	0.6	2.90	17.94
8.90	Peaches	0.75	6.68	16.55
5.64	Macadm.nuts	0.4	2.26	10.49
16.68	Apple Cider	1	16.68	30.99
15.68	Sweet/SourChick	0.8	12.54	29.13
8.90	Rice w/butter	0.8	7.12	16.55
4.83	CreamSpinach	0.8	3.86	8.97
0.56	Strawberries	0.9	0.51	1.05
6.21	Van. Pudding	0.8	4.97	11.54
17.18	Pineapple Drink	1	17.18	31.93
149.00	gm total water in food		121.78	276.84
	% water in food		81.7%	

Appendix B

Pre-requirement guidance 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

L1-RQMT ID	Requirement	Level 0 Trace	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

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