Membrane Distillation Bags for Water Recovery in Trash Compaction and Processing Systems

Krishnaswamy K. Rangan[1], Jacob Coppage-Gross[2], Jordan Terrazas[3], Michael McHale[4] and Tirumalai Sudarshan[5]
Materials Modification Inc., Fairfax, VA, 22031

The National Aeronautics and Space Administration's (NASA) crewed spacecraft missions use trash bags to store wastes derived from food, water, and other supplies. The trash bags occupy a large volume and present a significant logistical concern, especially for long duration missions. In order to reduce the volume of waste, control microbial growth and recover water, NASA has developed a heat melt compactor (HMC) unit. In this work, trash bags fabricated using selectively water permeable polymeric membranes were tested in a HMC unit. Recovery of water from solid waste and encapsulation of the waste after water recovery was achieved. Water was recovered from a waste simulant at various temperatures, and the total organic content (TOC) in recovered water was analyzed. The results showed up to a 50 - 85% reduction in TOC for the reclaimed water using membrane distillation bags (MD-BAGs) depending on the HMC process temperatures, the vacuum used, and pressure applied on the bag.

Nomenclature

$AgNO_3$	=	Silver Nitrate	*NASA*	=	National Aeronautics and Space Administration
AES	=	Advanced Exploration Systems	(LR)		Logistics Reduction
ARC	=	Ames Research Center	*PVA*	=	Polyvinyl Alcohol
HMC	=	Heat Melt Compactor	*SBIR*	=	Small Business Innovation Research
LDL	=	Lower Detection Limit	*SNC*	=	Sierra Nevada Corporation
LEO	=	Low Earth Orbit	*TOC*	=	Total Organic Carbon
$NaBH_4$	=	Sodium Borohydride	*ISS*	=	International Space Station

I. Introduction

Waste accumulation is a significant logistical concern for crewed space missions, especially with considerations for future long term missions to the Moon and Mars. On the International Space Station (ISS), trash is collected for storage in specific containers and then loaded onto supply vehicles to be burned on reentry to the atmosphere.[1] This is a viable solution for spacecraft orbiting the Earth but does not provide a feasible means of disposing or processing trash over long periods of time, as would be required for crewed missions beyond Low Earth Orbit (LEO) (e.g. Mars). The concept of the Heat Melt Compactor (HMC) was developed to sterilize and compact solid waste, while also collecting and recycling water for reuse. It will allow the crew to consolidate waste to a small fraction of its original size (<20%) and improve resource efficiency in missions where resource utilization is critical.[2] To assist NASA in the HMC process, Materials Modification Inc. (MMI) has developed a multifunctional waste disposal bag comprising of a unique, multilayered material that facilitates the collection of water and reducing the amount of organic contaminants present.[3,4] In this work, the Membrane Distillation bags (MD-BAGs) were tested using a HMC test unit built by Sierra Nevada Corporation (SNC)[5] to determine the optimal parameters for clean water recovery in space.

II. Heat Melt Compactor

The trash generated in International Space Station (ISS) are collected and compressed into small bags and then placed in larger bags.[6] The trash bags are sent back to Earth with a visiting logistics vehicles for disposal. The waste models

[1] Chief Chemist, 2809-K Merrilee Dr., Fairfax, VA 22031
[2] Senior Engineer, 2809-K Merrilee Dr., Fairfax, VA 22031
[3] Mechanical Engineer, 2809-K Merrilee Dr., Fairfax, VA 22031
[4] Engineering Intern, 2809-K Merrilee Dr., Fairfax, VA 22031
[5] President, 2809-K Merrilee Dr., Fairfax, VA 22031

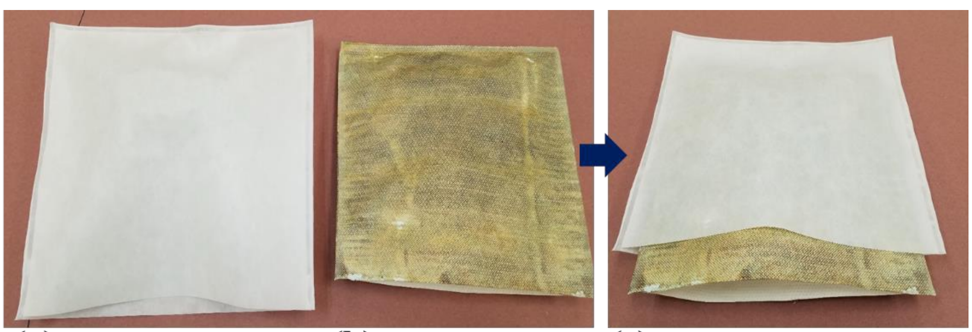
developed by Advanced Exploration Systems (AES) Logistics Reduction (LR) project estimated approximately 2600 kg (5730 lb) and 9 m^3 (318 ft^3) of waste generation for a 1-year mission with four-crew members.[6] This is a significant challenge for waste management in long duration space missions.

A waste management device called the Heat Melt Compactor (HMC) was developed by NASA to provide volume reduction, microbial stabilization, and resource recovery including water and potentially create a radiation shielding material from the trash. The history of HMC can be tracked by several publication dating back to 2003.[7-40] Various models of HMC were summarized by Fisher and Lee.[41] MMI has developed a membrane distillation bag (MD-BAG) to assist athe HMC process, which allowed water recovery with reduced organic content and minimum contamination of the HMC unit.[3,4] Here we present the study on the effects of HMC temperature, piston pressure, vacuum applied, and the use of dual bags on the total organic carbon (TOC) of the water collected.

III. MD-Bag Preparation

A proprietary breathable polymer membrane material was cut into rectangular pieces with dimensions of 12" x 25.5" for assembly of bags (Figure 1a). A coating solution of 4% polyvinyl alcohol (PVA) and 0.2% silver nitrate (AgNO3) in water was applied to the outer side of the membrane to impart antimicrobial properties while promoting selective permeability of water through the membrane (Figure 1b). An even layer of the PVA/$AgNO_3$ solution was applied with a paint brush and cured at 60 °C for 2 hours. Following this, the membrane was dipped in a solution of 2% sodium borohydride ($NaBH_4$) in water for 10 seconds, then cured a second time to reduce the silver nitrate to silver nanoparticles and graft the PVA onto the porous membrane. This process was adapted from prior work in preparing PVA stabilized silver nanoparticles on textiles.[42] The membrane was heat sealed around 3 edges to form a bag shape, and the final edge was sealed after loading with trash. For some bag samples, a double-sided pressure adhesive was used in place of heat sealing to close the bag after loading the trash.

Additional outer layers were used in some trials with the HMC (Figure 1c). A separate breathable hydrophobic material was cut into 13" x 27.5" rectangles, and heat sealed in a similar manner. No PVA coating was applied to this layer. The inner bag (once loaded) was placed inside the outer breathable layer and heat sealed on the final edge, forming a dual layer composite bag (Figure 1). Several different thicknesses of the breathable hydrophobic outer layer were tested, which were 240, 275, and 330 micrometers thick. Weights of the overall bags were ~50 g per bag. These bags can be used for storing other perishable and non-perishable items to maximize their benefit during a space mission.



(a) **(b)** **(c)**

Figure 1. Images of (a) outer breathable hydrophobic layer, (b) inner antimicrobial polymer bag, and (c) composite trash bag structure

A. Antimicrobila Tsting of MD-BAGs

In order to demonstrate the antimicrobial properties of the bags, Kirby Bauer tests were conducted on a variety of silver/PVA coatings on the MD-BAG. The test determines the antibiotic susceptibility of a strain of bacteria in question by preparing culture dishes for bacterial growth, placing the antimicrobial material to be tested on the dish, and using measurements of resulting zones of bacterial absence on the dish.[43] Each sample was 8 mm in diameter at the beginning. Membrane bags were treated with the following chemical treatment combinations: 1) PVA/$AgNO_3$,

2) PVA/$AgNO_3$ + $NaBH_4$/H_2O, 3) PVA/$AgNO_3$ + $NaBH_4$/H_2O + rinse, and 4) PVA/$AgNO_3$ + $NaBH_4$/Methanol. 0.5 mL of bacterial broth was used. The results of this test are provided in Figure 2 and Table 1.

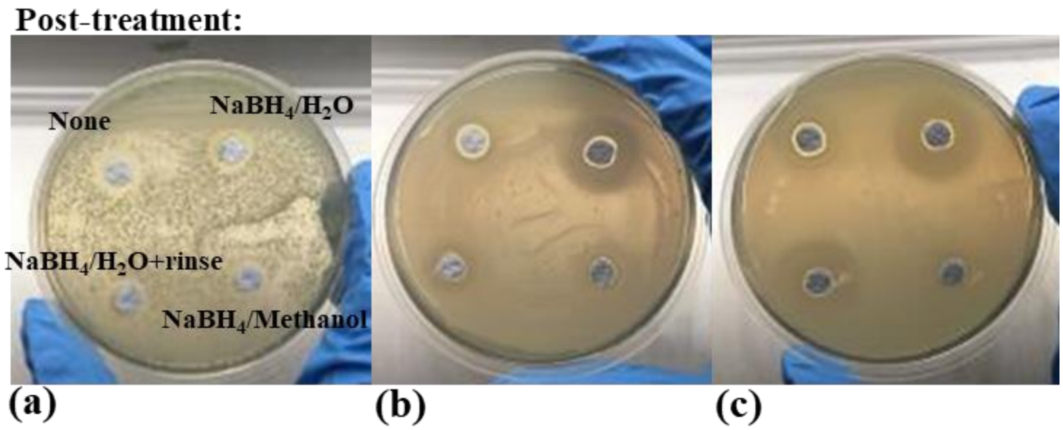


Figure 2. Zones of inhibition on PVA/$AgNO_3$ treated membranes (a) *S. epidermis*, (b) *E. coli, and* (c) *B. subtilis*

Table 1. Zones of inhibition for samples with different surface treatments after 24 hours

Strain	PVA/$AgNO_3$ (mm)	PVA/$AgNO_3$+ $NaBH_4$/H_2O (mm)	PVA/$AgNO_3$ + $NaBH_4$/H2O + rinse (mm)	PVA/$AgNO_3$ + $NaBH_4$/Methanol (mm)
E. coli	9	8	10	8
B. subtilis	9	9	8	8
S. epidermis	12	13	13	12

Antimicrobial properties in all four types of coatings were similar. Because there is no significant difference between the performance of the different coatings, PVA/Silver nitrate ($AgNO_3$) with a second dip in $NaBH_4$ was selected as the final method for ease of processing. In the case of the coating without the $NaBH_4$ treatment, leeching of the silver was observed during HMC operation. Adding an extra rinse step or having the $NaBH_4$ treatment in methanol complicated the procedure in terms of solvent disposal and number of steps, thus making the PVA/$AgNO_3$ → $NaBH_4$ in water the ideal preparation method for the silver coating on membrane bags.

IV. HMC Operation

Trash was prepared according to the composition outlined in prior literature.[41] A full list of individual items is given in Table 2. To prepare a waste sample for testing, all of the items were mixed in a bowl, with larger items cut into approximately square inch pieces. The mixture was loaded into the bag and sealed, followed by sealing of the outer layer, if applicable. The prepared trash mixture has a total mass of 497 g. The weight of the bags before and after testing was recorded to track water and organic chemical loss.

Table 2. Trash simulant recipe[41]

Item (Food)	Amt (g)	Item (Non-Food)	Amt (g)
Sausage	8.34	Salt	9
Apricots	3.89	T-shirt	84.2
Eggs	7.78	Towels	37.1
Orange Juice	16.87	Paper	6.2
Frankfurter	7.96	Dry Chem Wipes	14
Mac N'Cheese	9.91	Huggies	29.1
Tortilla	9.66	Nitrile Gloves	11
Peaches	8.9	Polyethylene Terephthalate	12.6

Nuts	5.64	Duct Tape	5.5
Apple Cider	16.68	Disinfectant Wipes	2
Rice	8.9	Foil	21.9
Creamed Spinach	4.83	Polypropylene	23.2
Vanilla Pudding	6.21	Polyethylene	61.1
Pineapple Juice	17.18	Nylon	21.9
Chicken	15.68	Chewing Gum	3.7
Stawberry	0.56	Silicone	0
		Toothpaste	1.8
		Shampoo	3.7

The HMC unit was set up according to the configuration shown in Figure 3. During operation, a loaded bag was placed in the compaction chamber and closed. The wired connections to the chamber were secured, and the vacuum line was routed to a steel trap, submerged in an ice bath. Program parameters were set on the adjacent laptop, outlined in Table 3.

Table 3. HMC operation parameters

Parameter	**Range**
Chamber Temperature	30 – 150 °C
Piston (Bellows) Pressure	0 – 110 kPa
Vacuum	4 – 67 kPa
Water Collection Trap (Condenser) Temperature	0 – 3 °C

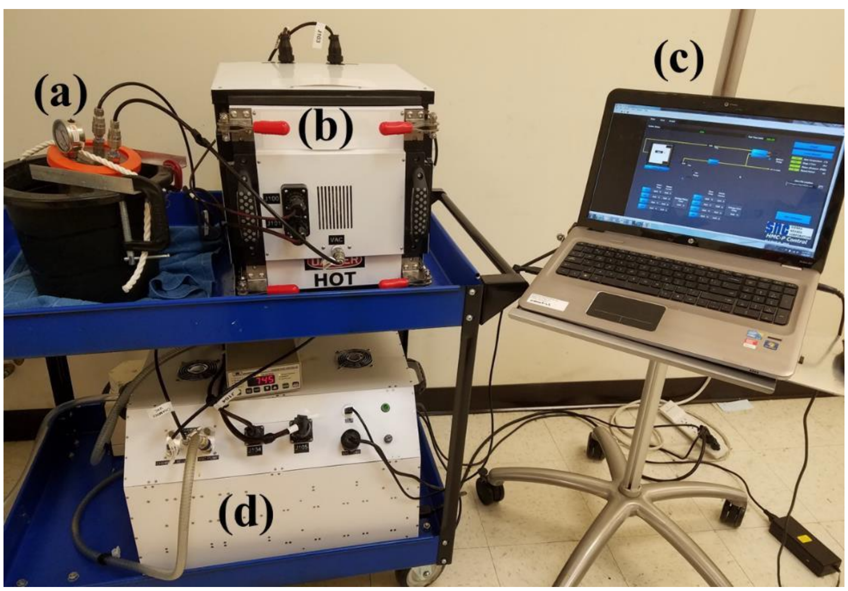


Figure 3. Image of HMC setup including (a) water collection trap (condenser), (b) compaction chamber, (c) laptop with Labview program for operation, and (d) control unit (vacuum pump behind unit)

A standard run profile is given in Figure 4, showing the water collection and consolidation stages. Water collection was performed over the course of 4 hours, while compaction was completed in 1-2 hours. Operation parameters were adjusted to evaluate the effects on water collection and purity. The collected water was sent to Pace Analytical, Beaver, WV for determination of total organic carbon (TOC) content by the SM5310 C-2011 method.[44]

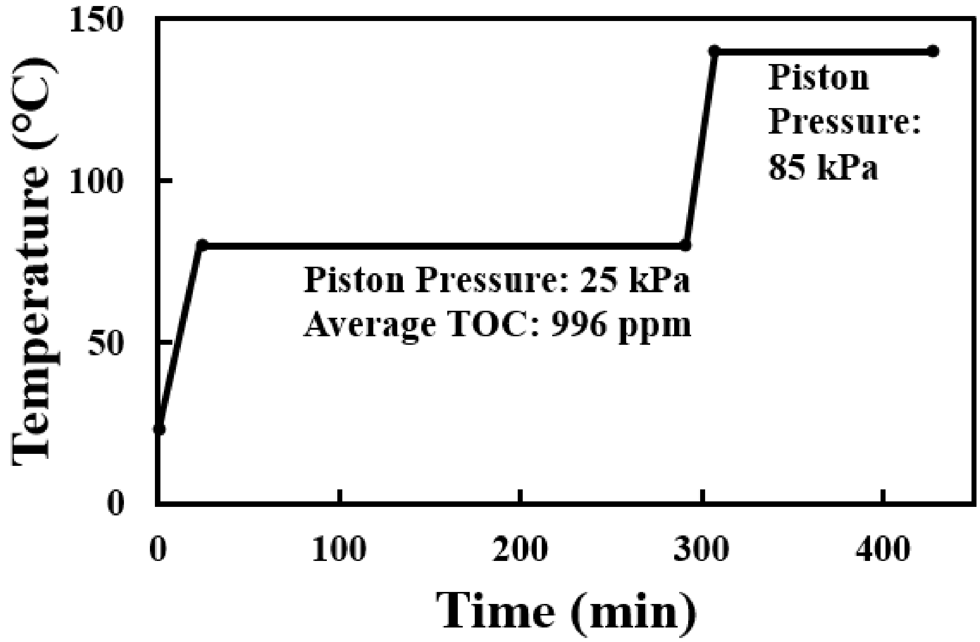


Figure 4. Temperature profile for HMC run

V. Experimental Results

Various runs were performed with the HMC using the outlined procedures and parameters above. TOC reduction was the primary objective, with modifications made to both the operating conditions and bag composition. An overview of completed runs (not in chronological order) is given in Figure 5, grouped according to common process parameters used.

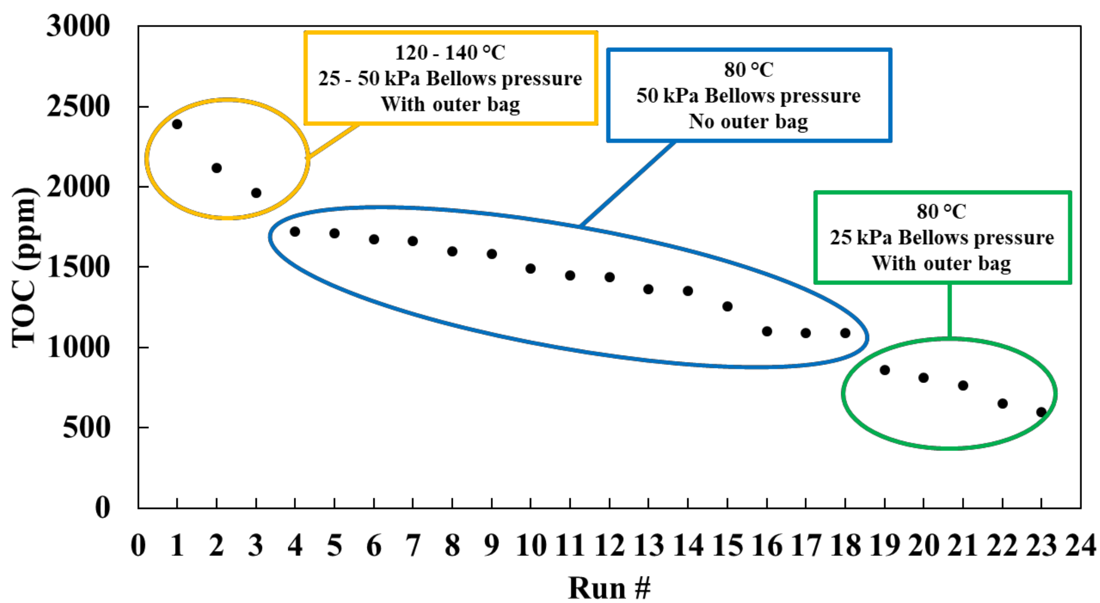


Figure 5. Run data in order of decreasing TOC values

A. Trash Control Run

In order to confirm the functionality of the membrane bag, running the HMC process without the bag should demonstrate the relative performance. However, concerns related to contamination of the vents and plugging of vapor lines are significant, as reported in prior HMC investigations.[4] Thus, a vacuum oven was used to test this concept, wherein the trash was placed inside the oven chamber and heated to 140 °C for a period of 3 hours, with an applied vacuum of ~150 mbar. Water was collected using a condenser, and its organic content was analyzed. The sample had a TOC of 5790 ppm, which is significantly higher than the value obtained using the bag at the same temperature. However, TOC data does not provide a full picture of the contamination caused to the oven without the membrane bag. After the run in the vacuum oven, large amounts of solid organic residue were left inside the oven, as well as in the tubes connecting to the condenser (Figure 6). Because of this result, a run in the HMC without the bag was not conducted, so as to avoid contamination of the system that could affect future runs. The amounts of organics that could be deposited throughout the vapor lines within and outside the HMC chamber could have significant detrimental effects on system performance.

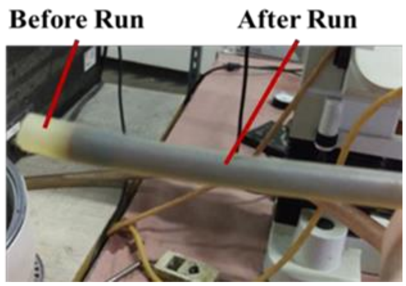


Figure 6. Image of gas line tube before and after vacuum oven run

B. Temperature Effect

As expected, 80 °C produces the lowest concentration of organics, although there is some variance depending on the bag selection and bellows pressure. At 140 °C, the TOC nearly doubles in value. TOC values are plotted as a function of temperature in Figure 7, showing a increase in organic content with increasing temperature. Even though there is a range of values at each temperature, the average value increases steadily. The higher level of organics can be attributed to more volatiles being released at higher temperatures, which ultimately end up in the water collected. While there is more water collected in higher temperature runs (~22% higher), the higher temperature likely causes many compounds in the food items to reach their boiling or decomposition temperature, and thus escape the bag.

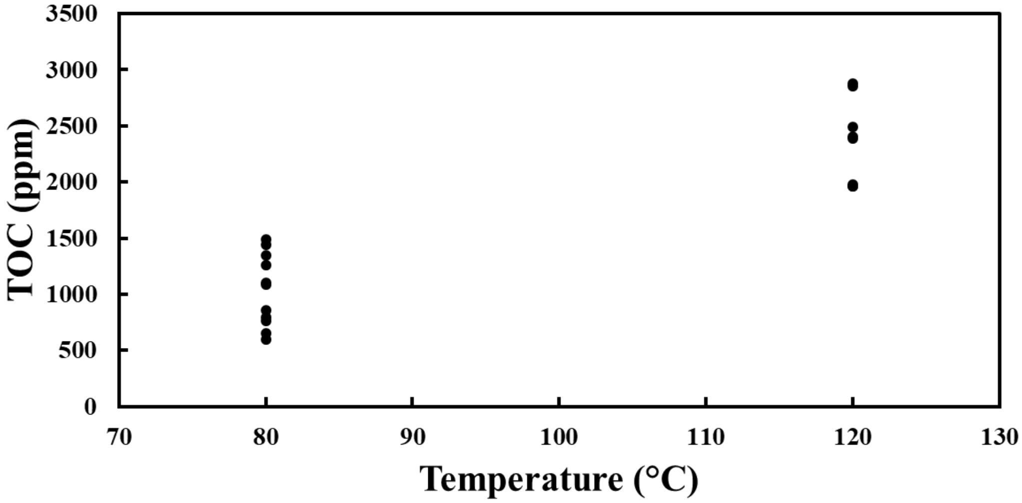


Figure 7. TOC data as a function of run temperature

C. Effect of Outer Bag

In addition to the effects of temperature, the use of the outer bag layer was also shown to reduce TOC (Figure 8). The average TOC level between runs using a single MD-BAG and those using the two MD-BAGs. The extra layer seems to provide additional resistance to organic transport while remaining permeable to water vapor, thus improving the purity of collected water.

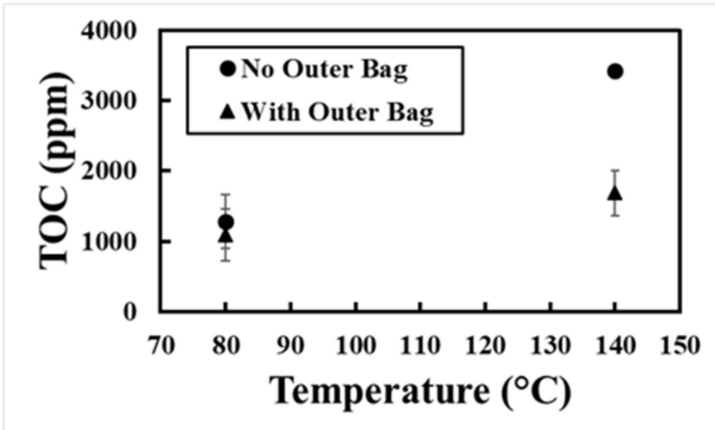


Figure 8. TOC comparison of double layered bags

The effect of the outer layer is also demonstrated by using a different thickness (Figure 9). With increasing outer layer thickness, the TOC is reduced. At the current highest thickness tested (330 µm) there was no appreciable reduction in water collected while there was a decrease in organic content. Additionally, the use of two outer bag layers resulted in similar TOC levels.

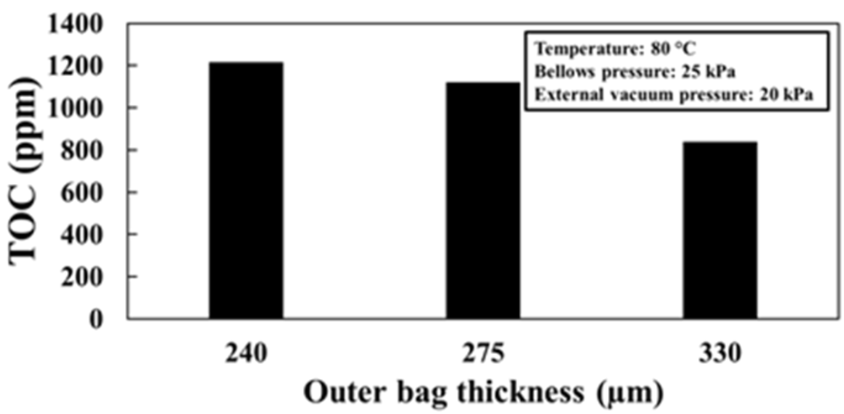


Figure 9. TOC as a function of outer layer thickness

D. Hourly Analysis of Water

To better understand the behavior of organic compound transport over the period of HMC operation, a standard HMC run using a regular trash batch in a coated bag was conducted at 140 °C, with the water removed from the collection vessel at one-hour intervals. The total amount of water collected was 129.04 g, which is consistent with typical runs at this temperature. The total organic carbon (TOC) of each removed sample was measured, and the total organics present (absolute) was calculated based on the volume of each aliquot (Table 4)

Table 4. Organic content data by the hour for 140 °C HMC run

Hour #	Amount of Water (mL)	TOC (ppm)	Organic Content (mg)
1	53.56	3220	172.5
2	50.85	1130	57.5
3	17.50	1944	34.0
4	7.13	2250	16.0

From these results, it is clear that a majority of the organic compounds in the trash leave very early on during the HMC cycle. While in the later hours TOC values remain high, there is significantly less water collected at these stages, resulting in inflated concentrations of organics. If the process can be run such that organic collection is high initially while water collection is low, the first pass of removed material can be discarded, leaving the water to be collected in later stages with much lower organic content. These tests should be replicated to confirm the tendency of organics to escape early in the collection process.

E. Identification of Trace Ions

Water collected from a run at 120 °C and 25 kPa bellows pressure using a double layered MD-BAG were analyzed at NASA ARC for TOC and trace ionic content. The analysis of ions remaining in the water is given in Table 5. Where lower detection limit (LDL) is listed, there was not enough of the ions present to be detectable. The results show that the collected water is nearly free of all ion contaminants, with only small amounts of ammonium, chloride, and sulfate present.

Table 5. Trace ion content of collected water

Ion Species	Concentration (ppm)
Na^+	LDL
NH_4^+	12.4
K^+	LDL
Mg^{2+}	LDL
Ca^{2+}	LDL
Cl^-	7.4
NO_2^-	LDL
Br^-	LDL
NO_3^-	LDL
PO_4^{3-}	LDL
SO_4^{2-}	4.0

F. Compaction of Trash

The average thickness of the bag was measured after each stage of the run, to show the volume reduction of trash (Figure 10). By the final stage, over 80% reduction in volume was achieved.

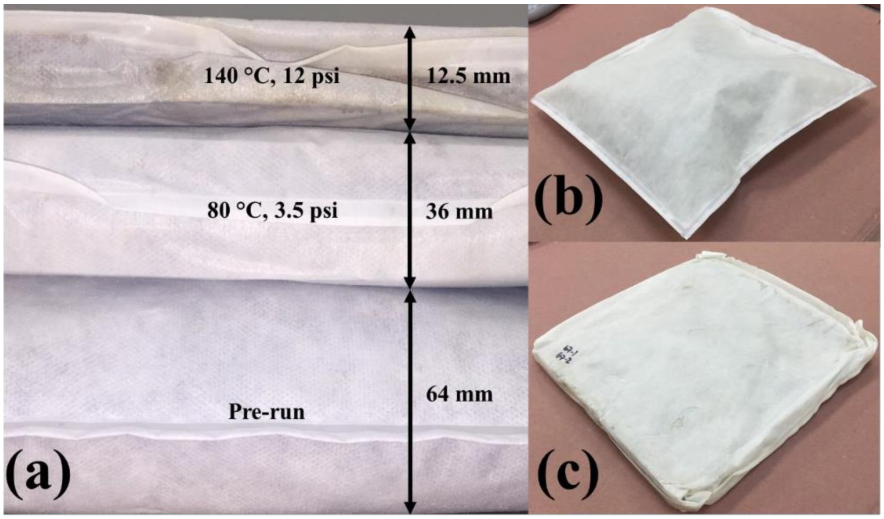


Figure 10. Images of (a) trash-filled bags before and after each run stage, (b) pre-run filled bag, (c) post-run filled bag

G. Microbial Control

Space mission trash has been reported to contain significant microbial populations that can grow if left untreated. The HMC technology can also support the sterilization of the compacted trash by heat treatment. After the water collection process, the microbial growth and proliferation were curtailed during the compaction stage. The processing temperature required for the sterilization of the trash simulant was determined by conducting the HMC process at various temperatures. Commercial spore strips (Mesa labs, Figure 11) were inserted into the trash before the HMC processing. These test strips were selected per the recommendation of previous studies conducted by NASA ARC.[4]

The strip was attached to the bag on the door side surface, which always has the lowest temperature reading according to the operation program. After HMC runs, the strips were sent to Mesa Labs for analysis. Table 6 shows the results for the runs at the various temperatures for the period of a run, which is typically four hours. A run temperature of 130 °C was required to decontaminate the spores.

Figure 11. Image of bacteria spore test strip

Table 6. Microbial control post-run testing

Run Temperature (°C)	Result
100	Fail
120	Fail
130	Pass

H. Future Work

There are several facets of this work that require further investigation before flight-readiness of this technology can be achieved. Notably, the sealing methods for the bag need to be amenable for astronauts working on the ISS or transport vehicle. Heat sealing is effective in the experimental procedure but requires too much volume to be viable in space. Other methods such as string closure or adhesives should be tested to ensure that the performance of the bag is not affected and that sealing of trash in space will be an easy task for the crew. The composition of the trash is also an area of interest. While the recipe given is meant to be a model for all waste produced on the ISS, there will undoubtedly be a high degree of variability in the trash from real missions. Experiments with different compositions of trash would be useful for determining any adverse effects due to changes in composition, i.e., higher food content, trash with very little water content.

VI. Conclusion

Through iterative experiments with the prototype HMC, the process was optimized for high water collection and low organic content. It was found that operation at 80 °C with a double layered bag and low bellows pressure produced the lowest TOC value (~500-800 ppm). Compaction of waste samples was also achieved, with >80% volume reduction, and prevention of microbial growth at compaction temperatures of 130 °C.

Acknowledgments

This work was supported by NASA's Small Business Innovation Research (SBIR) Program under the contract # NNX17CA07C (2017). The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of NASA. The authors would like to thank Dr. Jeffrey M. Lee of NASA Ames and John P. Wetzel of Sierra Nevada Corporation (SNC) for helpful discussions on the operation of HMC.

References

[1]Pace, G., Pisharody, S., and Fisher, J., "Plastic Waste Processing and Volume Reduction for Resource Recovery and Storage in Space," 33rd International Conference on Environmental Systems, SAE Technical Paper 2003-01-2369, 2003, doi:10.4271/2003-01-2369

[2]Linne, D.L., Palaszewski, B.A., Gokoglu, S., Gallo, C.A., and Balasubramaniam, R., Hegde, U.G., "Waste Management Options for Long-Duration Space Missions: When to Reject, Reuse, or Recycle," 7th Symposium on Space Resource Utilization, 13-17 January 2014, National Harbor, Maryland, AIAA Technical Paper 2014-0497, 2014.

[3]Rangan, K.K, Coppage-Gross, J., Frey, J., and Sudarshan, T., "Multipurpose Waste Disposal Bags for Heat Melt Compactor Application", 47th International Conference on Environmental Systems (ICES), ICES-2017-207, 2017.

[4]Rangan, K.K, Coppage-Gross, J., and Sudarshan, T., "Breathable Composite Materials for Water Recovery and Waste Management using Heat Melt Compactor" 48th International Conference on Environmental Systems ICES-2018-52, 2018.

[5]Wetzel, J.P., Surdyk, R.J., Klopotic, J., and Rangan, K.K., "Heat Melt Compactor Test Unit." 48th International Conference on Environmental Systems ICES-2018-318 8-12 July 2018, Albuquerque, New Mexico,

[6]Broyan, Jr. J.L., Schlesinger, T., Ewert, M.K., "Exploration Mission Benefits From Logistics Reduction Technologies." 46th International Conference on Environmental Systems ICES-2016-140, 10-14 July 2016, Vienna, Austria

[7]Pace, G., Pisharody, S., and Fisher, J., "Plastic Waste Processing and Volume Reduction for Resource Recovery and Storage in Space," 33rd International Conference on Environmental Systems, SAE Technical Paper 2003-01-2369, 2003, doi:10.4271/2003-01-2369.

[8]Pace, G. and Fisher, J., "Development of Plastic Melt Waste Compactor for Space Missions - Experiments and Prototype Design," 34th International Conference on Environmental Systems, SAE Technical Paper 2004-01-2378, 2004, doi:10.4271/2004-01-2378.

[9]Pace, G. and Fisher, J., "Testing and Analysis of the First Plastic Melt Waste Compactor Prototype," 35th International Conference on Environmental Systems, SAE Technical Paper 2005-01-3080, 2005, doi:10.4271/2005-01-3080.

[10]Pace, G.S. Fisher, J.W, "Compaction Technologies for Near and Far Term Space Missions," 36th International Conference on Environmental Systems, SAE Technical Paper 2006-01-2186, 2006. doi:10.4271/2006-01-2186.

[11]Hogan, J., Fisher, J., Pace, G., Litwiller, E. et al., "Development and Testing of a Breadboard Compactor for Advanced Waste Management Designs," 37th International Conference on Environmental Systems, SAE Technical Paper 2007-01-3267, 2007, doi:10.4271/2007-01-3267.

[12]Delzeit, L. and Fisher, J., "Construction of a Water-Absorbent, Zero-G, Compactor Trash Bag," 37th International Conference on Environmental Systems, SAE Technical Paper 2007-01-3262, 2007, doi:10.4271/2007-01-3262.

[13]Pace, G., Hogan, J., and Fisher, J., "Waste Compaction Technology Development for Human Space Exploration Missions," 37th International Conference on Environmental Systems, SAE Technical Paper 2007-01-3265, 2007, doi:10.4271/2007-01-3265.

[14]Fisher, J.W., Hogan, J.A., Delzeit, L., Liggett, T., Wignarajah, K., Alba, R., Litwiller, E., Pace, G., Fox, T.G. "Waste Management Technology and the Drivers for Space Missions," 38th International Conference on Environmental Systems, SAE Technical Paper 2008-01-2047, 2008.

[15]Pace, G.S., Delzeit, L., Fisher, J., "Testing of a Plastic Melt Waste Compactor Designed for Human Space Exploration Missions," 39th International Conference on Environmental Systems, SAE Journal Article 2009-01-2363, 2009.

[16]Pace, G., Fisher, J., Delzeit, L., Alba, R., Polonsky, A., "Development of a Plastic Melt Waste Compactor for Human Space Exploration Missions - A Progress Report," 40th International Conference on Environmental Systems, AIAA 10.2514/6.2010-6010, 2010.

[17]Marten, A., and Johnson, J., "Testing of a High Efficiency High Output Plastic Melt Waste Compactor Prototype." 41st International Conference on Environmental Systems (ICES), AIAA-2011-5125, 2011.

[18]Pace, G., Delzeit, L., and Fisher, J., "Testing of a Plastic Melt Waste Compactor Designed for Human Space Exploration Missions," 39th International Conference on Environmental Systems, SAE Int. J. Aerosp. 4(1):63-74, 2011, doi:10.4271/2009-01-2363.

[19]Strayer, R., Hummerick, M., Richards, J., McCoy, L., Wheeler, R., Roberts, M., "Characterization of Volume F trash from four recent STS missions: microbial occurrence, numbers, and identifications," 41st International Conference on Environmental Systems, 2011, doi: 10.2514/6.2011-5267

[20]Johnson, J., Marten, A., and Tellez, G., "Design of a High Efficiency, High Output Plastic Melt Waste Compactor." 42nd International Conference on Environmental Systems (ICES), AIAA-2012-3544, 2012.

[21]Pace, G., Fisher, J., Delzeit, L., Alba, R., Wignarajah, K., "Development of the Heat Melt Compactor for Waste Management during Long Duration Human Space Missions," 42nd International Conference on Environmental Systems, AAIA 10.2514/6.2012-3545, 2012.

[22]Strayer, R., Hummerick, M., Richards, J., McCoy, L., Roberts, M., Wheeler, R., "Characterization of Volume F trash from the three FY11 STS missions: Trash weights and categorization and microbial characterization," 42nd International Conference on Environmental Systems, 2012, doi: 10.2514/6.2012-3565.

[23]Strayer, R., Hummerick, M., Richards, J., McCoy, L., Roberts, M., Wheeler, R., "Microbial Characterization of Space Solid Wastes Treated with a Heat Melt Compactor," 42nd International Conference on Environmental Systems, 2012, doi: 10.2514/6.2012-3546.

[24]Delzeit, L.D, Fisher, J.W., Alba, R., Harris, L.C., "Chemical characterization of the Heat Melt Compactor Water Condensate and Effluent Gas," 43rd International Conference on Environmental Systems, 2013, (AIAA 2013-3395), 10.2514/6.2013-3395.

[25]Ewert, M.K., Broyan, J.L. Jr., "Mission Benefits Analysis of Logistics Reduction Technologies," 43rd International Conference on Environmental Systems, AIAA paper 2013-3383, 2013

[26]Fisher, J.W., Pace, G., Wignarajah, K., Harris, L.C., Delzeit, L.D., Alba, R., "An Assessment of the Water Extraction Capabilities of the Heat Melt Compactor," 43rd International Conference on Environmental Systems, AIAA 2013-3363,10.2514/6.2013-3363, 2013.

[27]Golliher, E.L., Gotti D.J., Rymut, J.E., Nguyen, B.K., Owens, J., "Evaporative Heat Transfer Mechanisms within a Heat Melt Compactor," 43rd International Conference on Environmental Systems, AIAA 2013-3392, 2013.

[28]Harris, L. C., Fisher, J.W., Pace, G., Wignarajah, K., Delzeit, L.D., Alba, R., "An Assessment Of The Water Extraction Capabilities Of the Heat Melt Compactor," 43rd International Conference on Environmental Systems, 2013, (AIAA 2013-3363) 10.2514/6.2013-3363

[29]Harris, L.C., Wignarajah, K., Alba, R., Pace, G., Fisher, J.W., "Characterization of Heat Melt Compactor (HMC)Compactor (HMC) Product Water," 43rd International Conference on Environmental Systems, (AIAA 2013-3394), 2013, 10.2514/6.2013-3394.

[30]Hummerick, M.P., Strayer, R.F., McCoy, L., Richards, J., Wheeler, R., Ruby, A.M., Fisher, J.W., "Heat Melt Compaction as an Effective Treatment for Eliminating Microorganisms from Solid Waste," 43rd International Conference on Environmental Systems, 2013, doi: 10.2514/6.2013-3364.

[31]Johnson, J., and Marten, A., "Testing of a High Efficiency High Output Plastic Melt Waste Compactor (HEHO-PMWC)." 43rd International Conference on Environmental Systems (ICES), AIAA-2013-3372, 2013.

[32]Jones, H.W., Pace, G., Fisher, J.W. "Managing Spacecraft Waste Using the Heat Melt Compactor (HMC)," 43rd International Conference on Environmental Systems, AIAA 2013-3362, 10.2514/6.2013-3362, 2013.

[33]Harris, L., Alba, R., Wignarajah, K., Fisher, J., Monje, O., Maryatt, B., Broyan, J., Pace, G., "Processing of Packing Foams Using Heat Melt Compaction,"44th International Conference on Environmental Systems, Texas Tech University Library http://repositories.tdl.org/ttu-ir/handle/2346/59665, 2014.

[34]Richard, A., Harris, L., Wignarajah, K., Fisher, J., Hummerick, M., Pace, G., Delzeit, L., Larson, B., "An Assessment of the Water Extraction Capabilities of the Heat Melt Compactor," 44th International Conference on Environmental Systems, Texas Tech University Library, http://repositories.tdl.org/ttu-ir/handle/2346/59666, ICES-2014-210, 2014

[35]Turner, M.F., Fisher, J.W., Broyan, J., Pace, G., "Generation 2 Heat Melt Compactor Development," 44th International Conference on Environmental Systems, Texas Tech University Library http://repositories.tdl.org/ttu-ir/handle/2346/59662, ICES-2014-024, 2014.

[36]Wetzel, J., Surdyk, R., and Johnson, J., "Plastic Melt Waste Compactor Integration and Testing." 45th International Conference on Environmental Systems (ICES), ICES-2015-322, 2015.

[37]Bahadori, A.A., Semones, E.J., Swan, B.G., "Heat Melt Compactor Puck Shielding Evaluation", SRAG NOTESRAG-COM-RDWK-2015-001, May 29, 2015.

[38]Gerges, D., "Feasibility Analysis of a Micro-Gravity Condensing Heat Exchanger Device for use on the Heat Melt Compactor," College of Engineering, Mechanical Engineering Department, Cleveland State University, http://www.osgc.org/pdf/2015-Proceedings.pdf, April 10, 2015.

[39]Golliher, D.L, Goo,J., Fisher J., “Water Recovery with the Heat Melt Compactor in a Microgravity Environment,” Proceedings of the 1st Thermal and Fluid Engineering Summer Conference, TFESC, August 9-12, New York City, USA, 2015.

[40]Wignarajah, K., Alba, R., Fisher, J.W., Richardson, T.J., “Shakedown Test of the Orbital Technologies PMWC for Performance in Treating Solid Wastes,” 45th International Conference on Environmental Systems, Texas Tech University Library, ICES-2015-211, 2015.

[41]Fisher, J.W., and Lee, J.M., Space Mission Utility and Requirements for a Heat Melt Compactor, 46th International Conference on Environmental Systems, ICES-2016-377 (2016).

[42]Montaser, A., Ramadan, M., and Hebeish, A. Facile way for synthesis silver nanoparticles for obtaining antibacterial textile fabrics, Journal of Applied Pharmaceutical Science, Vol. 6, 139-144 (2016)

[43]Bauer, A.W., Kirby, W.M.M., Sherris, and J.C., Turck, M., “Antibiotic Susceptibility Testing by a Standardized Single Disk Method,” The American Journal of Clinical Pathology, April 1966, https://www.asm.org/ccLibraryFiles/FILENAME /0000000295/105bauer.pdf

[44]Total Organic Carbon (TOC) (5310)/Persulfate-Ultraviolet or Heated-Persulfate Oxidation Method, Standard Methods for the Examination of Water and Wastewater