Performances of the Heat Melt Compactor System in Various Operational Scenarios

Jurek Parodi[1]
Bionetics Corporation, Yorktown, VA, 23693

Serena Trieu[2]
Logyx LLC, Mountain View, CA, 94043

Janine Young[3], Gregory Pace[4]
KBR, Houston, TX, 77002

and

Kevin R. Martin[5], Tra-My Justine Richardson[6], Jeffrey M. Lee[7]
NASA Ames Research Center, Moffett Field, CA, 94035

The Heat Melt Compactor (HMC) system has been developed to manage the waste generated on board spacecraft during long-duration missions. The quantity and composition of spacecraft trash depends upon the mission and can have a very high daily variability. This requires a flexible system able to manage extreme waste scenarios. Most missions will generate on average about one kilograms of trash per astronaut per day, derived mainly from the spacecraft logistics supplies and consisting of clothing, food & beverage residues, packaging, paper, plastic, hygiene wipes, and many other personal or scientific items used and discarded by the crew. Uncontained and unprocessed waste is a health hazard and a habitat storage problem. However, trash also contains valuable resources such as water. HMC is designed to provide volume reduction, microbial safening and stabilization, water recovery, and radiation shielding material. The final byproduct generated by HMC is a sterilized tile with the consistency of hard plastic that can be safely handled, easily stored, and used for radiation protection. This paper provides the summary of an extensive campaign of testing performed using the HMC system to simulate different nominal and extreme operational scenarios and to generate the data necessary to finalize requirements for proto-flight hardware to be deployed to an International Space Station (ISS) EXPRESS Rack.

Nomenclature

A = ampere
AES = Advanced Exploration Systems
ARC = Ames Research Center
ECLSS = Environmental Control Life Support Systems
EXPRESS = EXpedite the PRocessing of Experiments to Space Station
CatOx = catalytic oxidizer
CMU = Compress Melt Unit
CTB = cargo transfer bag
DI = deionized
DMLE = double middeck locker equivalent
Gen1 = 1st Generation HMC
Gen2 = 2nd Generation HMC
HC = high cloth
HL = high liquid

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[1] Aerospace Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[2] Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[3] Chemical Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[4] Senior Mechanical Engineer, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[5] Science Payload Project Manager, Flight Systems Implementation Branch, M/S 240A-3, NASA ARC, Moffett Field, CA 94035.
[6] Research Physical Scientist, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.
[7] Solid Waste Management Lead, Bioengineering Branch, M/S 239-15, NASA ARC, Moffett Field, CA 94035.

HMC = Heat Melt Compactor
ISS = International Space Station
LEO = low earth orbit
LRR = Logistics Reduction and Repurposing
MCTB = multipurpose cargo transfer bag
MMI = Materials Modification Inc.
*N*m* = Netwon meter
NextSTEP = Next Space Technologies for Exploration Program
Nom = nominal
psi = pounds per square inch
psia = pounds per square inch, absolute
PTFE = polytetrafluoroethelyne
RTD = resistance temperature detector
TCPS = Trash Compaction Processing System
TEC = thermoelectric cooler
TOC = total organic carbon
USN = United States Navy
VES = Vacuum Exhaust System

I. Introduction

THE Heat Melt Compactor (HMC) is a waste management system developed by National Aeronautics and Space Administration (NASA) to support manned missions both in low earth orbit (LEO) and in deep-space. Currently, the only waste management practice implemented on the International Space Station (ISS) is the manual compaction of waste into plastic bags that are sealed with duct tape to form "football-shaped" packs that are then stored in cargo transfer bags (CTBs) and eventually loaded into the cargo module, which is incinerated during atmospheric reentry. The current practice does not provide any significant volume reduction, any microbial safening and stabilization, nor any recovery of critical resources such as water. The HMC system is designed to provide those capabilities by compacting spacecraft trash and by generating a dried, sterilized byproduct with the shape of a tile and with the consistency of hard plastic that can be safely handled by the crew, easily stored onboard, and even used for radiation protection once available in large quantities.

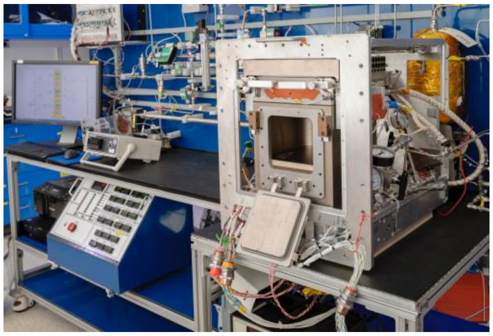


Figure 1. Gen 2 HMC at NASA ARC.

The first HMC prototype, known as Gen 1, was developed at the NASA Ames Research Center (ARC) over a number of years starting in 2003. It was based on the Compress Melt Unit (CMU) hardware developed for the United States Navy (USN). The USN's system was designed to process large amounts of plastic-rich trash generated onboard warships and thus was large, heavy, and had high energy consumption. The compress melt technology looked promising for human space flight due to some similarities in the trash models generated onboard ships and spacecraft, the large volume reductions achieved, and the safety provided to the crewmembers handling the final trash byproduct. Thus, the HMC Gen 1 was developed focusing on microgravity operations to demonstrate the capability of compressing spacecraft waste, recovering water, and melting the plastic to generate a hard and stable byproduct. The resulting trash-disk had a circular shape with an 8" diameter and achieved an approximately ten-fold reduction in the volume of the initial trash loaded into the system.[1]

A second generation HMC unit, known as Gen 2, was developed starting in 2010 as part of the Advanced Exploration Systems (AES) Logistics Reduction and Repurposing (LRR) Project with an emphasis on increased thermal efficiency, reduced power needs, and minimum overall mission cost.[2] The main objective of the Gen 2 prototype is to serve as a ground-based precursor to a flight demonstration unit by proving the feasibility of processing trash in different mission scenarios while operating within the constraints of an ISS Express Rack and to acquire long-term operational data for identification of technical risks and mitigation strategies. The compress-melt portion of the Gen 2 hardware is packaged to conform to the dimensions of a double middeck locker equivalent (DMLE) EXPRESS Rack Payload (~22" x 22" x 18"). However, in order to provide operational flexibility during ground testing, most sensors, control electronics, and water/gas separation and collection hardware are installed externally to the simulated EXPRESS Rack[3] volume. A MATLAB and Simulink control logic provides semi-autonomous operation and extensive data acquisition. The system was designed to process approximately 810 cubic inches of hand compacted trash within a 14 hour operational cycle, to function using no more than 500 Watts, and to rely only on avionics air for cooling. The geometry of the tiles is a 9" x 9" square with rounded corners to maximize the efficiency of storage within the volume of a multipurpose cargo transfer bag (MCTB). Moreover, because of their high content in hydrogen mainly from plastics, food, and cloth components, the tiles can be used to provide additional radiation shielding.[4] The 9" x 9" tile size was also influenced by taking into account the maximum thermal load that can be dissipated in an EXPRESS Rack (heating power and avionics air cooling) during the nominal 14-hour operational cycle. The compaction ring and the ram are made of stainless steel and are separated from the main body through a thermal breaker made of

Torlon to minimize waste heat. All of the surfaces in contact with trash are covered with nonstick coatings. A mechanical scissor jack is used to provide compaction pressure and to enable piston-ram position control, which allows the ram to move to specified positions during the compaction process and to facilitate tile ejection when complete.

II. HMC Gen 2 Hardware Modifications and Operations

The design of the HMC system as used during the testing described in this paper has partially changed from the original Gen 2 hardware build. The modified HMC hardware still provides compaction and melt functions mainly as originally designed. However, the Water Recovery subsystem and the Gas Contaminant Control subsystem have been largely modified to accommodate samples collection under new testing conditions, to overcome problems encountered during extensive continious operations, and due to defective components and/or inherent design flaws discovered during testing.

Operations begin with manually loading the trash into the compaction chamber and closing the hatch. The system then processes the trash through compacting and heating at sub-atmospheric pressures. As soon as the water contained in the trash reaches the boiling point and starts evaporating, it separates from the trash and leaves the compaction chamber to be condensed and collected in the Water Recovery subsystem. The trash is then maintained under compaction after the water content is largely removed. The heating temperatures within the chamber are then increased to melt the plastics and sterilize the trash. Throughout the entire heating process, gaseous compounds are released by the trash components. Most of these compounds are not condensable at either near-freezing temperatures or cryogenic temperatures, and thus they pass through the Water Recovery subsystem and flow into the Gas Contaminant Controls subsystem where they are oxidized by the Catalytic Oxidation (CatOx) subsystem. The now oxidized gases, if sufficiently safe for release, can finally be vented to space or released back into the crew cabin. (Note that the possible operational scenarios of “vent-to-space”, “vent-to-cabin”, or some combination of the two has not yet been decided at the time of this testing campaign.) Because the CatOx subsystem requires a near atmospheric pressure to operate properly, the Gen 2 unit was designed to allow the introduction of cabin air to be used as a sweep gas to dilute the effluent gases coming off the trash from the compaction chamber. Finally, once the sterilization phase is complete, avionics air is used to cool the system down to ambient temperature before the compacted and sterilized trash tile is removed from the compaction chamber.

The main problems encountered during preliminary testing of the Gen 2 HMC system were a greatly reduced compaction force, vacuum and thermal leaks throughout the system, and unsuitable construction materials employed in some of the subsystems, which affected both the final quality of the tile and the quality and mass balance of the recovered water.

Despite the original design requirement for a total compaction force of at least 50 psi when processing a batch load of 500 grams of trash, the system was able to deliver only around 20 psi even when combining both the mechanical force provided by the multi-link scissor mechanism/ram assembly and the pneumatic force delivered by the sub-atmospheric pressure.

For this reason, the existing Harmonic Drive actuator, model FHA-11C, which was able to generate a maximum torque of 11 N*m, was replaced with the next larger version, model FHA-14C, capable of generating a torque up to 28 N*m and operating at a maximum current of 12.3 A during the initial transient and a continuous current of 4.4 A. The type and dimensions of the miniature hollow shaft actuator were limited mainly by the maximum applicable torque of the bearings of the multi-link scissor mechanism and by the footprint available in the DMLE.

The gas pressure within the compression chamber needs to be maintained as low as possible throughout the entire duration of the operational cycle in order to achieve an overall higher compaction force on the trash and to reduce the boiling point of water. Water collection at lower temperatures has the advantages of both decreasing the heating power required overall, and most importantly lowering the concentration of contaminants in the condensed water recovered. The minimum absolute pressure originally achieved at the plenums of the waste processing chamber was above 3.5 psia, even after replacing the existing Alcatel Adixen 2005I rotary vane pump with a more powerful Edwards nXDS10iC dry scroll vacuum pump, capable of achieving an ultimate pressure of 10^{-4} psia. An inspection of all the system’s components and plumbing lines to pinpoint major air leaks led to the identification of the dynamic vacuum seal gland on the ram as not being air-tight due to incorrect tolerances. Thus, a 1.75” thick, tile-shaped aluminum plug with a silicone o-ring with 70A durometer was made and used to vacuum seal the compression chamber by positioning it on top of the ram during operations. The adoption of the plug helps to achieve a minimum gas pressures within the compression chamber as low as 0.3 psia. However, because of the thickness of the plug, the ram cannot be fully extended within the chamber, leading to a reduction of the maximum mechanical compaction force delivered by the multi-link scissor mechanism.

Two other major air leaks were identified. The torlon thermal breaker that separates the stainless steel compaction ring from the lower section of the compaction chamber, which encloses the multi-link scissor mechanism, and the Buna gasket sealing the lid to the compaction ring. The leak through the thermal breaker increased over time because of the degradation of the high-temperature silicone RTD sealant used between the Torlon and the stainless steel sections. Unfortunately, the proper redesign of the thermal breaker and upper section of the compaction chamber to include gaskets would have involved a major disassembly of the entire Gen 2 system and would have drastically impacted the project schedule. Thus the team opted to externally cover the leaky areas with Kapton tape, wherever reachable. The leak through the lid seal has also worsened over time because of wear and tear of the Buna gasket during continuous opening and closing to remove tiles. Excessively tight tolerances and the sharp edge of the lid caused the gasket to be chewed as the lid moved over it repeatedly. Luckily, the lid gasket is easily replaceable and thus has been substituted with a new resized silicone gasket, which has shown much better resistance to wear and tear.

The Water Recovery subsystem was initially composed of an external condenser made of a copper coil submerged in an ice bath and connected to a graduated cylinder. After a few test runs of the Gen 2 system done with both trash and deionized water only, the color of the water samples collected started to look blue/greenish. Chemical analysis of the samples confirmed the presence of copper oxide, likely caused by corrosion of the copper coil. Moreover, the maximum water recovery rate was around 70% and the subsystem required frequent ice replacement. Thus, the ice bath condenser has been replaced by a thermoelectric cooler (TEC) consisting of a CP-110 cold-plate cooler with a LC-SSX1 stainless steel heat exchanger from TE Technology. A programmable temperature controller with two thermistors regulates the output power to the TEC using pulse-width modulation. The temperature of the thermoelectric cooler is set at 3 °C to prevent deposition of ice within the heat exchanger when the gas flow is saturated with steam, which gradually reduces the effective diameter of the pipe and eventually completely blocks the orifice, thus interrupting the gas flow and increasing the pressure of the system. The total water recovery rate achieved by the TEC itself in this operating condition is around 70%. In order to capture the missing volume of water, a second stage condenser operating at sub-freezing temperature, composed of a cold trap filled with dry ice, has been added in series to the TEC. The two stages combined allow a water recovery rate of approximately 100%.

Figure 2. Delaminated tile caused by adhesion to the lid.

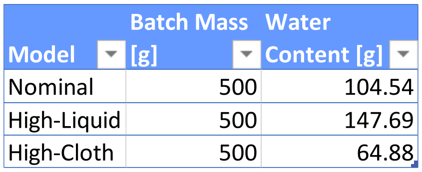
The top surface of the ram, the bottom surface of the lid, and the inner surface of the compaction chamber are coated with a 0.002” thick nonstick material intended to prevent adhesion of the trash and allow easy removal of the final tile. The coating used in Gen 2 is NEDOX SF-2 from General Magnaplates, a nickel-phosphorus alloy with impregnated polymer particles characterized by high chemical stability and lasting non-stick and antistatic properties. However, during early testing of the Gen 2 system the processed trash adhered to the heated surfaces of the ram and the lid, often preventing the lid from opening and requiring the use of a hydraulic jack to generate enough shear force to move the lid. Because of the high shear forces taking place in this process, the tiles were subject to delamination and thus their final quality was compromised as shown in Figure 2. Moreover, once the lid was opened, often pure mechanical force was not sufficient to manually separate the trash from the ram without structurally damaging the tile. A blade had to be used in these conditions with the risk of damaging not only the tile itself but also the non-stick coating of the ram. Figure 3 shows the ram with residues of melted plastic and gunk from caramelized food and juices sticking to its surface. In a microgravity environment, it is expected to be even more difficult to manually separate the processed trash tile from the compacting surfaces because of the induced forces and moments on the astronauts, which would require additional restraints to make the removal of the tile possible. In order to minimize the need of any external mechanical forces when removing the processed trash tile from Gen 2, two sheets of 0.015” thick polytetrafluoroethelyne (PTFE) membrane were used, the first one deposited on the top surface of the plug before loading the batch of trash in the compaction chamber and the second one deposited on top of the trash itself, separating the trash from the surface of the lid. The PTFE membrane sheets completely eliminated any trash adhesion to the heated surfaces of the ram and the lid, allowing an easy removal of the final tile from the system. Each sheet can be reused on average of 10 consecutive

Figure 3. Residues of melted plastics and gunk on the ram surface.

times. The only reason for replacement is damage from lacerations, which might occur when separating the membrane from the final processed trash tile. Different nonstick coatings are being investigated for the future flight demonstration unit.

III. Testing

Table 1. Water volume contained in each trash batch.



Model	Batch Mass [g]	Water Content [g]
Nominal	500	104.54
High-Liquid	500	147.69
High-Cloth	500	64.88

Testing was conducted to evaluate the performances of the HMC Gen 2 system ito collect gas and water samples necessary to identify the compounds coming off the trash during the compacting and melting process, and to determine their most extreme concentrations. In order to protect the CatOx system from poisoning caused by certain gaseous compounds, and to determine the potentially most hazardous operational scenario, the entire Gas Contaminant Controls subsystem was bypassed. This prevented the gas mixture released by the trash from being diluted by the nominal sweep gas as well as from being oxidized prior to analysis. The P&ID of the system as used during the testing campaign is shown in Figure 4.

The quantity and composition of spacecraft trash depends upon the mission and can have a very high daily variability. The HMC system is designed to process both wet and dry waste scenarios. Most missions will generate on average about one kilogram of trash per astronaut per day, derived mainly from the spacecraft logistics supplies and consisting of clothing, food & beverage residues, packaging, paper, plastic, hygiene wipes and other items used and discarded by the crew. The trash contains a substantial amount of plastic and water trapped in food residue, paper products and other items. In order to account for the trash variability, one nominal and two extreme scenarios (high-liquid and high-cloth) have been identified and their respective models have been used during testing to evaluate and compare the system's performances in a repeatable way. Table 1 summarizes the total mass of water contained in each model.

The nominal waste model is based on actual trash that is commonly generated aboard the ISS but with certain components removed that are not expected to be present on an advanced space exploration mission. Unused sugary drinks and high cloth contents that characterize the two extreme waste model variations are of interest because they might challenge the performances of the HMC system. Sugary drinks represent a significant challenge to the seals of the compaction chamber and to downstream ancillary hardware because of the generation of sticky residues in he areas where the liquid is dewatered and then caramelized during the heating process. This caramelized byproduct hardens and binds to hardware surfaces and it can compromise system functionalities and/or require frequent system maintenance. In particular, this issue has been observed not only on the surfaces of components located in the processing chamber, but also in downstream components such as tubing, heat exchangers and sensors. On the other hand, the sticky byproduct can have a beneficial effect on the waste by helping the processed trash achieve a higher density and maintain a more compacted form, thus resulting in a better quality tile. The high-liquid model used in the Gen2 testing has a total water content that is 148 g in a 500 g batch, or 30 % of the total trash sample mass and 9 %

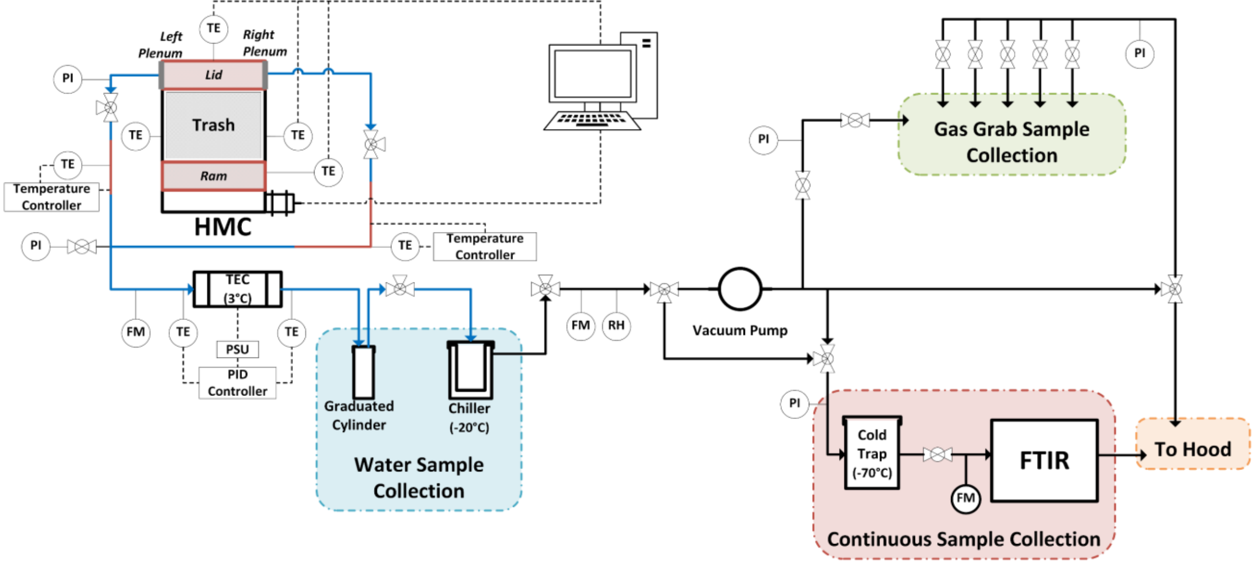


Figure 4. P&ID of HMC Gen2 system as used during testing campaign.

Table 2. Summary matrix of runs performed during testing campaign.

Trash Model	Tile #	Run Date	MMI Bag	Water Analysis	Gas Analysis	In-line FTIR
High-Cloth	HC1	12/12/19	no	ARC	KSC, SGS Galson	no
High-Cloth	HC2	12/19/19	no	ARC	KSC, SGS Galson	yes
High-Cloth	HC3	01/15/20	no	ARC	JSC, KSC	no
High-Cloth	HC4	02/26/20	yes	ARC		yes
High-Liquid	HL1	12/02/19	no	ARC, JSC	JSC, KSC, SGS Galson	no
High-Liquid	HL2	12/05/19	yes	ARC, JSC	JSC, KSC, SGS Galson	no
High-Liquid	HL3	01/06/20	no	ARC	KSC, SGS Galson	no
High-Liquid	HL4	01/09/20	no	ARC	KSC, SGS Galson	no
High-Liquid	HL5	01/23/20	no	ARC	JSC, KSC	no
High-Liquid	HL6	02/18/20	no	ARC		yes
High-Liquid	HL7	03/03/20	no	ARC		yes
High-Liquid	HL8	03/05/20	yes	ARC		yes
Nominal	Nom1	10/17/19	no	ARC, JSC	ARC, JSC, KSC	no
Nominal	Nom2	10/23/19	no	ARC	KSC, SGS Galson	no
Nominal	Nom3	11/06/19	no	ARC	KSC, SGS Galson	no
Nominal	Nom4	11/21/19	no	ARC	KSC, SGS Galson	no
Nominal	Nom5	02/10/20	no	ARC	KSC	yes
Nominal	Nom6	02/24/20	yes	ARC	JSC	yes

higher compared to the nominal model. The cloth mass represents the 25 % of the total trash mass and is 3 % lower compared to the nominal model.

The introduction of large quantities of cloth into the system also represents a significant challenge. In fact, a larger mass of cloth means a more limited amount of binding components in the trash mix, which are provided mainly by molten plastics and the previously mentioned caramelized sugary drinks. A high-cloth scenario is obtained when whole clothing items such as t-shirts, shorts, and pants are processed in the system during a single cycle. This could occur for example if all astronauts discarded their clothing at the same time and decided to process all those garments in 1-day instead of evenly distributing them between multiple cycles. A four person crew could discard up to eight garments simultaneously for a total up to 1.2 kg of cloth. For comparison, the high-liquid model used in the Gen 2 testing has a total water content that is 64.9 g in a 500 g batch, or 13 % of the total trash sample mass (this is 8 % lower than the nominal model), whereas the cloth mass represents 66 % of the total trash mass (about 38 % higher than the nominal model).

A comprehensive testing campaign was conducted to evaluate the overall functionality of the HMC Gen 2 system. Multiple experiment runs were performed gathering extensive data to quantify the volumetric trash reduction and the water recovery, and to collect gas and water samples for chemical and biological analysis. The overall objectives of this work are: 1) to determine key performance metrics that include volume of recovered moisture, specific power used during the heating process, volume and density of the final tile, 2) to identify the compounds that are outgassed by the trash and their concentrations, 3) to determine during which phase of the processing these gases are produced, and 4) to identify the compounds that are captured in the recovered water and their concentrations. Several trash runs and deionized (DI) water runs were performed during the year to test the system as a whole or to evaluate single subsystems. Variations in melt temperatures, bellow pressures, waste mass, and cycle times were tested. Following each of these tests, testing parameters were adjusted for subsequent runs based upon lessons learned from the previous

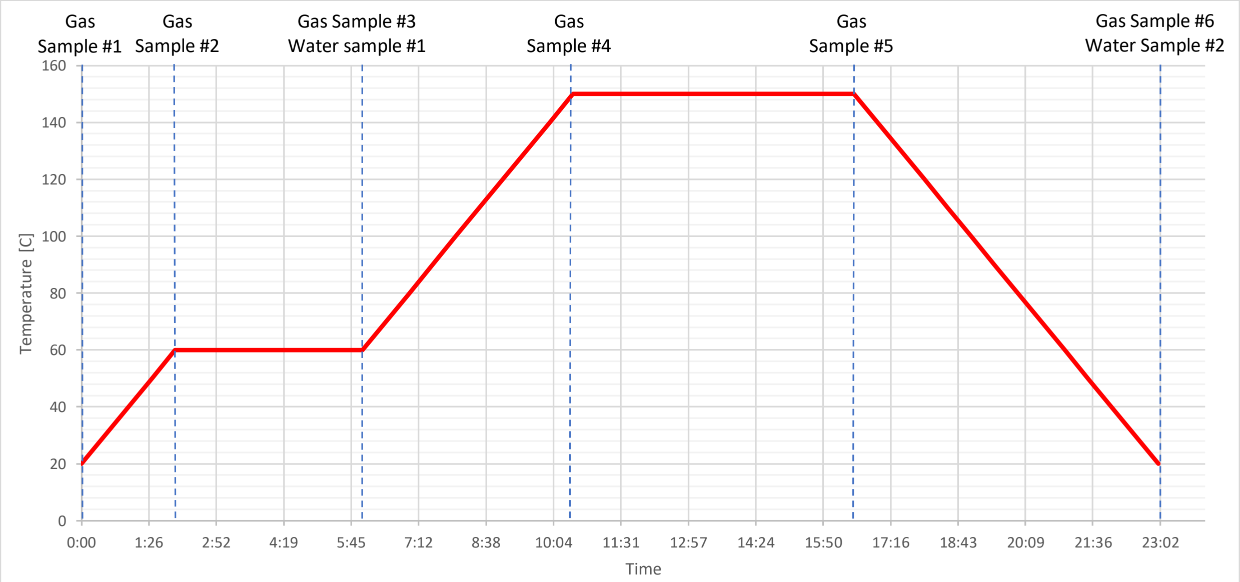


Figure 5. Simplified generic trash run with samples collection points.

testing until an ideal temperature profile was established and optimal sampling times were identified. This paper summarizes only the results of test runs conducted by implementing the optimized temperature profile and sampling times, with the only variable parameters being the trash composition and the use of free trash versus trash contained in polymeric bag permeable to water vapor provided by Materials Modifications Inc. (MMI part number MMI-2386). The matrix in Table 2 lists and characterizes the runs of the testing campaign described in this paper. Each run listed in the matrix was followed by a wash run with DI water with collection of water samples before starting the next trash run.

The general test procedure consists of preparing a 500 g batch of trash ersatz, loading the chamber, running the compaction and heating cycle, collecting water and gas samples, and finally removing the cooled tile when complete. During this testing campaign, the trash was loaded into the compacting chamber from the top by opening the lid instead of from the front port since the presence of the aforementioned improvised plug does not allow enough clearance. After the lid is closed and secured, the vacuum pump is turned on, the ram is pulled up, and the heaters are turned on. The ram compacts the trash while the heaters in the ram, the lid, and the side walls heat the trash. In order to reduce heat losses to the environment, in particular due to the side walls heaters that are located on the exterior of the compaction chamber, the core unit is covered with insulation panels. When the boiling point is reached, the water in the trash is boiled and the vapor is carried out of the chamber through the side plenums and condensed in the Water Recovery subsystem, where it is collected primarily in the TEC and secondarily in the chiller and the cold trap. The temperature of the system is set and maintained at 60°C, slightly above the boiling point, during the first phase of the run, until most water leaves the trash. Subsequently, the temperature is increased to 150°C, and after a hold time of about 3 hours which is sufficiently long and hot enough to sterilize the trash, the heaters are turned off and the compacted trash is cooled. The plastic components in the heated trash start to melt at approximately 130°C, bonding to the other constituents. During the cooling phase, the plastic solidifies generating a physically stable and compact tile.

Since the trash releases volatiles initially present in its components or produced by their breakdown during the heating phase, 6 grab gas samples are collected in canisters and/or desorption tubes respectively at 1) the beginning of the run, 2) when reaching the boiling point, which corresponds to the beginning of the low-temperature phase, 3) after most water has been collected at the end of the low temperature phase, 4) when reaching 150°C, which determines the beginning of the high-temperature sterilization phase, 5) at the end of the high-temperature phase, and 6) at the end of the run after the system has cooled to room temperature. Moreover, an additional blank sample is collected for each run. When using the in-line FTIR instrument, the gas released by the trash is continuously collected and analyzed by the instrument before being vented into the lab vent hood. All the gas samples are collected downstream of the vacuum pump in order to pressurize the canisters with enough volume for analysis.

Since volatiles may also be contained in the condensed water, water samples are collected at the end of the low-temperature phase from the graduated cylinder after the TEC and at the end of the run from both the graduated cylinder after the TEC and from the chiller and cold trap. Sometimes the volume of water collected from the chiller and/or cold-trap is not enough for analysis. Water samples are also collected during the wash run with DI water that follows each trash run. During the wash run, 200 ml of DI water are poured into a dedicated container within the processing chamber and heated to the boiling point. A set of condensed water samples is collected in the middle of the run and a second set of samples is collected again at the end of the run.

Figure 5 shows the simplified, generic temperature profile of each trash run and the times at which water and gas samples are collected.

IV. Results

The results of the trash runs listed in Table 2 are grouped below based on the trash model and include representative plots and pictures of the final product tiles. The plots show the relationship between the following parameters during the heat melt compaction process: chamber temperatures, moisture recovery after the TEC, ram force and position, chamber pressure, gas flow after the plenums, total pressure applied on the trash, and total heating power.

The average chamber temperature is the average of the lid and ram temperatures. The wall heaters and thermocouples are mounted externally to the core unit and thus the wall temperatures have a much faster response compared to the lid and ram temperatures, which is not representative of the thermal profile of the trash within the chamber. During the first transient from room temperature to 60 °C and then during the second transient from 16 °C to 150 °C, the trash is subject to a vertical temperature gradient within the chamber, with the bottom portion of the trash being cooler compared to the top portion until equilibrium is reached. The different temperature gradients are due to the larger heat capacity of the ram and plug, compared to the heat capacity of the lid. The set temperature of 60 °C is reached at both the ram and the lid, and maintained until there is no more condensed water coming out from the TEC. However, the set temperature of 150 °C is reached only at the lid during the duration of the run. Additional hours of operation would be necessary to reach 150 °C also at the ram.

Although the entire core unit is covered with multiple layers of insulation panels to minimize convection, a portion of the heat provided by the external heaters is wasted to the environment. The total heating power includes the power provided by the ram, lid, and wall heaters. However, it does not include the power provided by the external strip heater used to heat the plumbing between the plenums and the TEC to avoid condensation in the line. The total power is maximum during the transient heating phases and starts decreasing after the set temperatures are reached.

The total pressure on the trash tile is calculated as the sum of the mechanical ram force and of the chamber pressure provided by the vacuum pump. The ram force usually increases over time due to the thinning of the tile, which is caused mainly by mass reduction and minorly by the melting of plastics. A thinner tile means a higher position of the ram within the compaction chamber. Both the absolute pressure and the gas flow increase in correspondence to the boiling of the water and evacuation of the generated steam. They both decrease after all the water has been boiled off of the trash and remain approximately constant thorough the rest of the run.

The quality of each tile is usually defined by its density, the higher being the density, the better the quality. The density is directly proportional to the final mass of the tile and inversely proportional to its thickness. As expected, an increasing total pressure produces higher density tiles.

The results of the gas analysis are reported in a separate paper, titled *Effluent Gas Collection and Analysis of the Heat Melt Compactor's Trash Processing* by Young et al.[5] The results of the water analysis will be reported in a separate paper in 2021.

A. Nominal Model

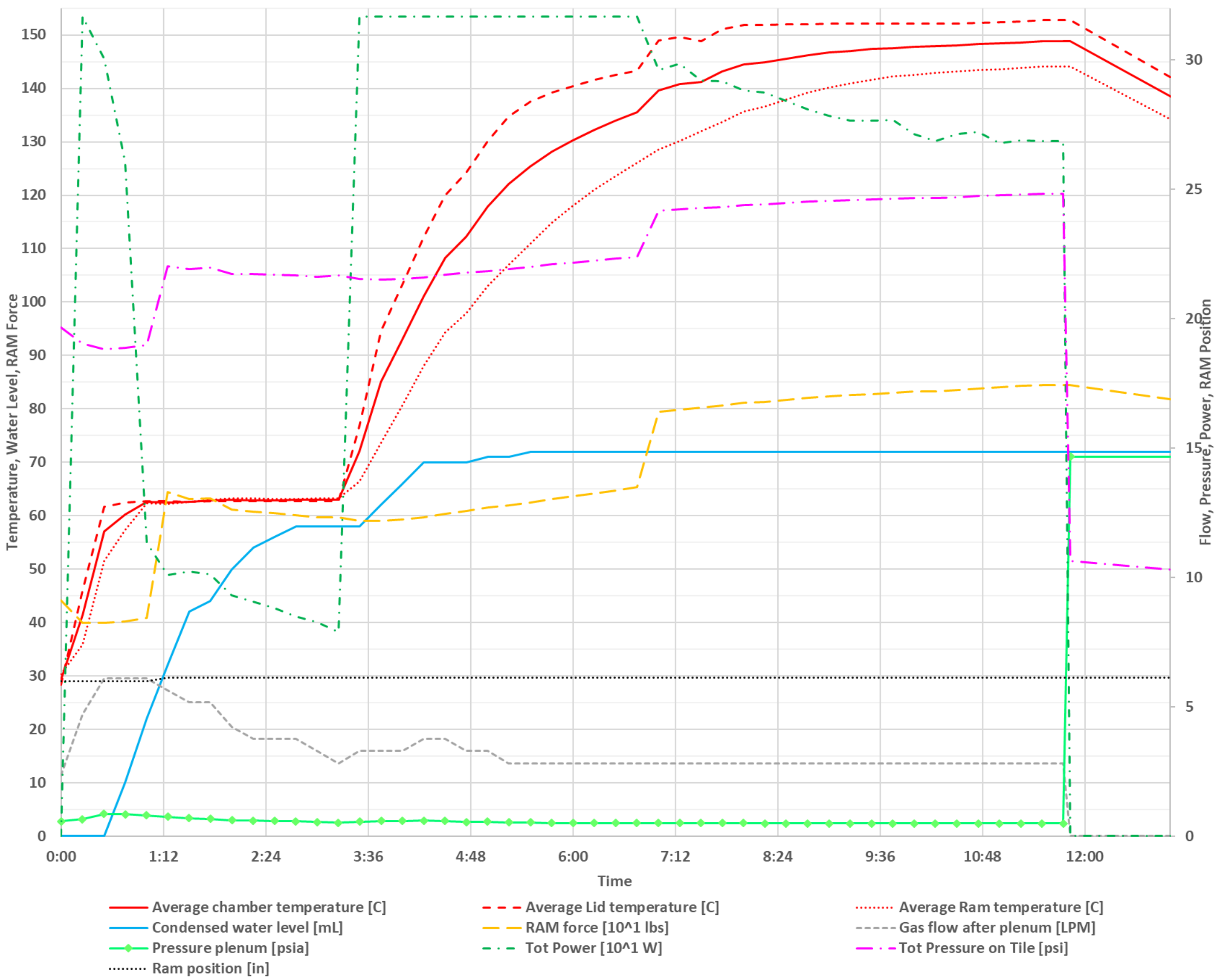


Figure 6. Resulting data for Nom2 run.

Figure 6 shows the resulting data for the Nominal batch #2 run (Nom2), which generated the tile with the highest density among the nominal runs, equivalent to 463.3 kg/m^3. The average density of tiles generated with the nominal trash model is 442.67 kg/m^3, with a standard deviation of 18.29 kg/m^3. The Nom2 tile also has the lowest thickness among the tiles generated using the nominal model, equivalent to 0.65”. The average thickness of nominal tiles is 0.69”, with a standard deviation of 0.04”. The maximum mechanical force achieved during the Nom2 run is 842 lbs. The maximum ram force achieved on average during nominal runs is 738.8 lbs, with a standard deviation of 84.1 lbs. The lowest absolute pressure achieved during the Nom2 run is 0.49 psia. The minimum absolute pressure obtained on average during nominal runs is 0.42 psia, with a standard deviation of 0.08 psia.

Figure 7. Top (top) and bottom (bottom) of Nom2 tile.

The mass loss of trash measured during the Nom2 run is 108.3 g, which is higher than the total theoretical water content of the trash itself. This discrepancy can be explained by the detachment of solid particles from the tile during the compaction process and during post-processing handling. In particular, it has been noted that caramelized/burnt trash components, believed to be food, are very brittle and debris of them are often seen on top of the plug after removal of the tile and/or trapped between the plug and the inner walls of the compaction chamber. Another factor that contributes to the mass loss is the offgassing of other gas contaminants from the trash components, however this has a negligible effect when compared to the loss attributed to water. The average mass loss obtained for the nominal trash runs is 105.6 g, with a standard deviation of 4.04 g and is approximately 1% higher than the theoretical initial moisture content.

The volume of water recovered has a high variability both between runs and within the runs themselves. In fact, the total volume of water collected during the Nom2 run is 90.6 ml, which corresponds to 86.7% of the total theoretical moisture initially contained in the trash. Of this volume, 56.2 ml, or 62% was collected after the TEC during the low-temperature phase, 11.4 ml, or 12.6% was collected after the TEC at the end of the high temperature phase, and the remaining 23 ml, or 25.4% was collected at the end of the run from the cold trap and chiller. The total volume collected on average during nominal trash runs is 93.64 ml, or 89.6% of the total theoretical moisture contained in the trash, with a standard deviation of 21.1 ml. On average, 43.1 ml of water with a standard deviation of 14.8 ml and corresponding to 46% of the total, is collected after the TEC at the end of the low-temperature phase, 24.7 ml with a standard deviation of 20.18 ml and corresponding to 26.4% of the total is collected after the TEC at the end of the high-temperature phase, and 25.8 ml with a standard deviation of 16.7 and corresponding to 27.6% of the total is collected from the cold trap/chiller a the end of the run.

Figure 8. Nom6 trash loaded into the MMI bag.

The variability of water recovery within the run may be explained by the way the different trash components are loaded into the chamber. When the “wet” trash components are located closer to the plenums and/or closer to the heating surfaces, more water is collected during the low-temperature phase. Whereas when the “wet” trash components are located in the middle of the puck, more water is collected during the high-temperature phase. When the water evaporation rate is higher, part of the vapor bypasses the TEC and is condensed in the chiller/cold trap. The variability of water recovery from run to run is due mainly to the condensation of water in non-heated plumbing lines and/or volumes in correspondence of sensors.

Figure 7 shows the top and bottom of the Nom2 tile. There are visible voids on the sides, which may be of concern in microgravity due to the potential detachment of brittle debris, delamination, and absorption of water with potential bacterial growth.

The final nominal trash run, Nom6, has been performed using a custom-made bag manufactured in-house using a foot-operated heat sealer with the material provided by MMI. The dimensions of the bag were approximately

10” by 10” by 10” an the mass was 68.5 g. The trash has been loaded into the bag (see Figure 8) and, after closing it by manually rolling the top section of its side walls, the bag was inserted in the HMC compaction chamber and processed following the standard operational profile. Figure 9 shows the resulting Nom6 tile. The density of tile is 448.3 kg/m^3, within the range of the other nominal trash tiles. The thickness of the tile is 0.8”,which is higher compared to the other nominal tiles due to the additional bag material. The maximum mechanical force and the lowest absolute pressure achieved during the Nom6 run are respectively 632 lbs and 1.28 psia. The mass loss of trash measured during the Nom6 run is 103.5g and the total volume of water collected is 110.6 ml, which corresponds to 105.8% of the total theoretical moisture initially contained in the trash. Of this volume, 46.3 ml, or 44.3% was collected after the TEC during the low-temperature phase, 40.8 ml, or 39% was collected after the TEC at the end of the high temperature phase, and the remaining 23.5 ml, or 22.5% was collected at the end of the run from the cold trap and chiller. Although the total volume of moisture collected during the Nom6 run is within the range of the other nominal runs, the rate at which the vapor was permeating through the MMI bag was much lower, 11.58 ml/h compared to 22.9 ml/h during the Nom2 run. Thus, the duration of the low-temperature phase was drastically increased.


Figure 9. Top of the Nom6 tile.

The use of the MMI bag reduces several operational risks particularly concerning use in microgravity. First, it prevents trash components from getting trapped between gaskets and o-rings during the loading process of the compaction chamber. Second, it eliminates any trash adhesion to the heated surfaces of the ram and the lid (even without the use of PTFE sheets) allowing for easy removal of the final tile from the system. Finally, it prevents delamination and detachment of solid particles from the tile during the compaction process and after removal of the tile and during post-processing handling and storage. However, including the bag material causes about a 12% mass penalty when processing 500 g batches of trash.

B. High-Liquid Model

Figure 11 shows the resulting data for the High-Liquid batch #1 run (HL1), which generated the tile with the highest density among the high-liquid runs, equivalent to 518.19 kg/m^3. The average density of tiles generated with the high-liquid trash model is 480 kg/m^3, with a standard deviation of 25.64 kg/m^3. The HL1 tile also has the lowest thickness among the tiles generated using the high-liquid model, equivalent to 0.54”. The average thickness of high-liquid tiles is 0.58”, with a standard deviation of 0.03”. The maximum mechanical force achieved during the HL1 run is 801 lbs. The maximum ram force achieved on average during high-liquid runs is 776.67 lbs, with a standard deviation of 115.23 lbs. The lowest absolute pressure achieved during the HL1 run is 0.46 psia. The minimum absolute pressure obtained on average during high-liquid runs is 0.67 psia, with a standard deviation of 0.39 psia.


Figure 10. Top (top) and bottom (bottom) of HL1 tile.

The mass loss of trash measured during the HL1 run is 137.5 g, which corresponds to 93.1% of the total theoretical water content of the trash itself. The average mass loss seen for the high-liquid trash runs is 139.55 g, with a standard deviation of 2.04 g and approximately 5.5% lower than the theoretical initial moister content.

The volume of water recovered has been pretty consistent from run to run but had a some variability within the runs themselves depending on the temperature and phase. The total volume of water collected during the HL1 run is 136 ml, which corresponds to 92.1% of the total theoretical moister initially contained in the trash. Of this volume, 88.2 ml, or 64.9% was collected after the TEC during the low-temperature phase, 14.8 ml, or 10.9% was collected after the TEC at the end of the high temperature phase, and the remaining 33 ml, or 24.3% was collected at the end of the run from the cold trap and chiller. The total volume collected on average during high-liquid trash runs is 140.07 ml, or 94.8% of the total theoretical moisture contained in the trash, with a standard deviation of 5.12 ml. On average, 86.15 ml of water with a standard deviation of 26.97 ml and corresponding to 61.5% of the total, is collected after the TEC at the end of the low-temperature phase, 29.93 ml with a standard deviation of 32.64 ml and corresponding to 21.4% of the total is collected after the TEC at the end of the high-temperature phase, and 23.98 ml with a standard deviation of 10.72 and corresponding to 17.1% of the total is collected from the cold trap/chiller a the end of the run. Similar to the nominal case, the variability of water recovered within the run is likely explained by the way the different trash components are loaded into the chamber. Figure 10 shows the top and bottom of the HL1 tile.

Two high-liquid trash runs, HL2 and HL8, were performed using custom-made bags manufactured in-house using material provided by MMI. The dimensions of the bags were approximately 10” by 10” by 10”.

Figure 12 shows the resulting HL8 tile. The density of tile is 520.94 kg/m^3, which is the highest value measured for all the high-liquid trash tiles. The thickness of the tile is 0.64”, which is higher compared to the other high-liquid tiles due to the additional bag material. The maximum mechanical force and the lowest absolute pressure achieved during the HL8 run are respectively 793 lbs and 1.19 psia.

The mass loss of trash measured during the HL8 run is 142.24 g and the total volume of water collected is 145.8 ml, which corresponds to 102.5% of the total theoretical moisture initially contained in the trash. Of this volume, 40.5 ml, or 27.8% was collected after the TEC during the low-temperature phase, 88.1 ml, or 60.4% was collected after the TEC at the end of the high temperature phase, and the remaining 17.2 ml, or 11.8% was collected at the end of the run from the cold trap and chiller. Although the total volume of moisture collected during the HL8 run is within the range of the other high-liquid runs, the rate at which the vapor was permeating through the MMI bag was much lower, 12.46 ml/h compared to 20.75 ml/h during the HL1 run during the low-temperature phase. The MMI material used in the HL8 run had a yellowish anti-microbial coating that affected the color of the water collected after the TEC during the low-temperature phase. The analysis of the water samples is not available at this time.

The mass of the material for the custom-made bag was 72.7 g and corresponds to approximately a 15% mass increase when processing 500 g batches of trash.

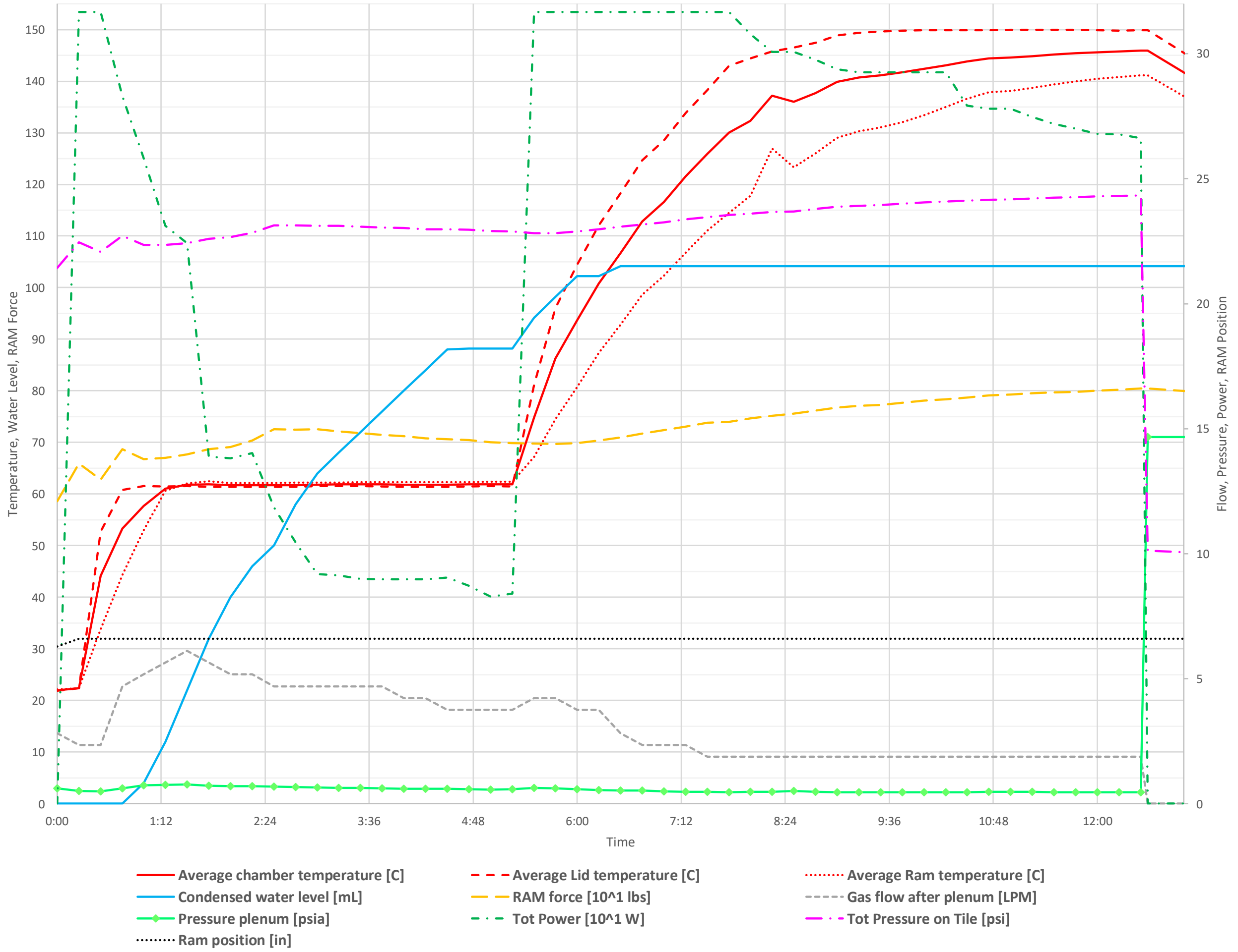


Figure 11. Data results from the HL1 run.

C. High-Cloth Model

Figure 12. Top of HL8 tile.

Figure 13 shows the resulting data for the High-Cloth batch #2 run (HC2), which generated the tile with the highest density among the high-cloth runs, equivalent to 391.03 kg/m^3. The average density of tiles generated with the high-cloth trash model is 367.37 kg/m^3, with a standard deviation of 20.78 kg/m^3. The HC2 tile also has the lowest thickness among the tiles generated using the high-liquid model, equivalent to 0.87". The average thickness of high-cloth tiles is 0.93", with a standard deviation of 0.05". The maximum mechanical force achieved during the HC2 run is 723 lbs. The maximum ram force achieved on average during high-cloth runs is 759.33 lbs, with a standard deviation of 78.12 lbs. The lowest absolute pressure achieved during the HC2 run is 0.43 psia. The minimum absolute pressure obtained on average during high-cloth runs is 0.44 psia, with a standard deviation of 0.03 psia.

The mass loss of trash measured during the HC2 run is 57.8 g, which corresponds to 89.1% of the total theoretical water content of the trash itself. The average mass loss obtained for the high-cloth trash runs is 58.5 g, with a standard deviation of 1.76 g and approximately 9.8% lower than the theoretical initial moisture content.

The total volume of water collected during the HC2 run is 52.2 ml, which corresponds to 80.5% of the total theoretical moisture initially contained in the trash. Of this volume, 30.2 ml, or 57.9% was collected after the TEC during the low-temperature phase, 4 ml, or 7.7% was collected after the TEC at the end of the high temperature phase, and the remaining 18 ml, or 34.5% was collected at the end of the run from the cold trap and chiller. The total volume

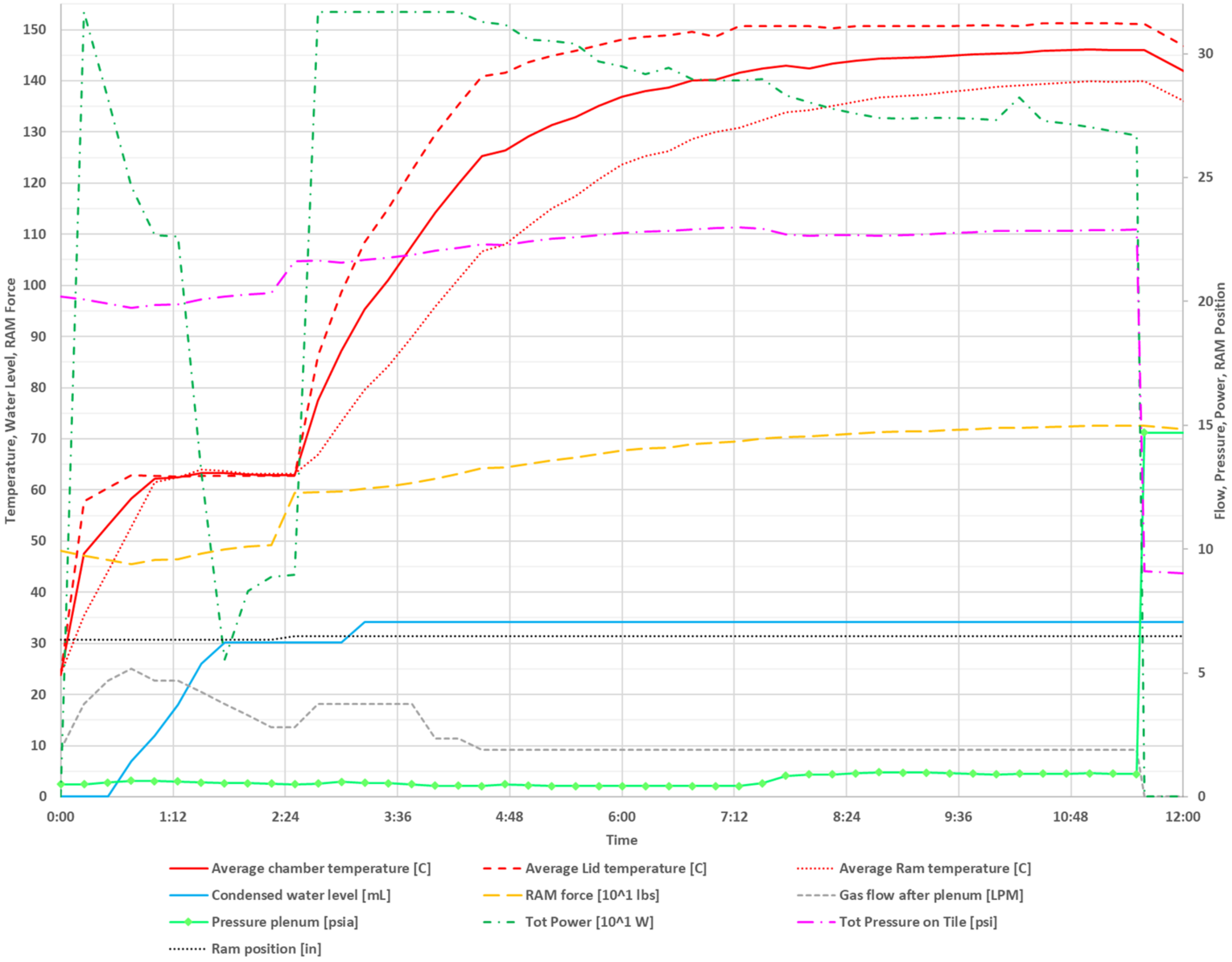


Figure 13. Data results from the HC2 run.

collected on average during high-liquid trash runs is 57.8 ml, or 89.1% of the total theoretical moisture contained in the trash, with a standard deviation of 5.33 ml. On average, 24.13 ml of water with a standard deviation of 8.91 ml and corresponding to 41.8% of the total, is collected after the TEC at the end of the low-temperature phase, 7.33 ml with a standard deviation of 3.09 ml and corresponding to 12.7% of the total is collected after the TEC at the end of the high-temperature phase, and 26.33 ml with a standard deviation of 8.2 and corresponding to 45.6% of the total is collected from the cold trap/chiller a the end of the run.


Figure 14. Top (top) and bottom (bottom) of HC2 tile.

Figure 14 shows the top and bottom of the HC2 tile.

Unfortunately, the results from the water samples collected during high-liquid trash runs are still not available at this time.

A high-cloth trash run, HC4, was performed using custom-made bags manufactured in-house using the material provided by MMI. The dimensions of the bags were approximately 10” by 10” by 10”.

Figure 15 shows the resulting HC4 tile. The density of tile is 368.46 kg/m^3 and its thickness is 1.07”, which is higher compared to the other high-cloth tiles due to the additional bag material. The maximum mechanical force and the lowest absolute pressure achieved during the HC4 run are respectively 703 lbs and 1.25 psia.


Figure 15. Top of the HC4 tile.

The mass loss of trash measured during the HC4 run is 57.4 g and the total volume of water collected is 57.5 ml. Of this volume, 12.1 ml, or 21% was collected after the TEC during the low-temperature phase, 36.4 ml, or 63.3% was collected after the TEC at the end of the high temperature phase, and the remaining 9 ml, or 15% was collected at the end of the run from the cold trap and chiller. Similar to the other runs done with a bag, the vapor permeated at a lower rate, approximately 4.94 ml/h during the low-temperature phase.

The mass of the material for the custom-made bag was 70.4 g and corresponds to approximately a 14% mass increase when processing 500 g batches of trash.

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