Heat Melt Compactor Test Unit

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The Heat Melt Compactor (HMC) is a logistical waste management system designed to process trash in support of human operations in space. Processing includes compressing the waste into a manageable tile and recovering water from the waste. Previous developmental systems have been built to demonstrate and evaluate the effectiveness of this HMC waste compaction and water recovery technique. The HMC Test Unit leverages the design from these previous models to assemble a streamlined version that will be used to evaluate implementation of permeable bags to encase the trash during compaction. The HMC Test Unit design focuses on compaction of the trash and recovery of water using heat, partial vacuum, and compression. The unit is sized to accommodate an 11.5-inch square tile, somewhat larger than the 9-inch square tiles processed using the NASA ARC second generation HMC (GEN2) and smaller than the 16-inch square tiles processed using the SNC Plastic Melt Waste Compactor (PMWC). Following design, fabrication, and checkout, the unit will be delivered for testing the application of permeable bags.

Nomenclature

ARC = Ames Research Center
BVAD = Baseline Values and Assumptions Document
CM = Crew Member
EXPRESS = EXpedite the PRocessing of Experiments to Space Station
GEN2 = Generation 2 (second generation NASA ARC HMC)
GLS = Gas/Liquid Separator
HMC = Heat Melt Compactor
ISS = International Space Station
LRR = Logistics Reduction and Repurposing
MMI = Materials Modification, Inc.
PMWC = Plastic Melt Waste Compactor
SBIR = Small Business and Innovative Research
SNC = Sierra Nevada Corporation

I. Introduction

LONG-DURATION space exploration missions will require efficient stowage of waste as well as effective reclamation of water. Current primary waste systems cannot reclaim water or effectively reduce the volume of trash generated by astronauts. Heat Melt Compactor (HMC) technology under development at Sierra Nevada Corporation (SNC) and at NASA Ames Research Center (ARC) provides a means to recover nearly all the water entrained in the trash for further use as well as to significantly reduce trash volumes. Initial development efforts focused on demonstrating the principle of heat melt compaction and verifying the feasibility of this technology. Recent more advanced efforts have resulted in the fabrication, assembly, and testing of HMC units that generate sizable tiles through the heat melt compaction process. NASA ARC evolved their HMC design[1],[2] to a second

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generation (GEN2) system which processes trash to generate 9-inch square tiles. SNC matured their design[3] under a NASA Phase II Small Business and Innovative Research (SBIR) grant for a Plastic Melt Waste Compactor (PMWC) that reduced the trash into a 16-inch square tile. The HMC Test Unit leverages the design from these previous models to assemble a streamlined version that will be used to evaluate implementation of permeable bags being developed by Materials Modification, Inc. (MMI) to encase the trash during compaction. The HMC Test Unit design focuses on compaction of the trash and recovery of water using heat, partial vacuum, and compression. The unit is sized to accommodate an 11.5-inch square tile, somewhat larger than the 9-inch square tiles processed using the NASA ARC GEN2 and smaller than the 16-inch square tiles processed using the SNC PMWC.

II. Background

SNC's PMWC was developed as a variant of HMC technology to recover nearly all the water entrained in the trash for further use as well as to significantly reduce trash volumes. The PMWC was designed to be a stand-alone system for use in the International Space Station (ISS) EXPRESS rack, requiring only access to power, data, and air cooling interfaces. The PMWC works by simultaneously heating and compressing trash to first remove the water and then to melt plastic within the trash. The melted plastic reduces the trash into a square tile, approximately one inch thick. In addition to the tiles facilitating the storage of trash, the polyethylene in the melted plastic gives the tile the potential ability to act as a radiation shield.

The objective of the PMWC project was to develop and test a fully functional, stand-alone unit to assess the plausibility of fabricating a unit that could generate a large 16-inch square tile, including the assessment for manufacturability of a large vacuum-tight square processing chamber, and evaluating the ease or difficulty of removing the tile. The project also included the evaluation of the thermal efficiency of an HMC using aluminum over stainless steel, and of the system design in general with the large cube-shaped chamber and limited ability to insulate due to the confined dimensions within an EXPRESS rack.

A. Prototype PMWC

The prototype PMWC system[4,5] includes two separate enclosures designed to fit within an ISS EXPRESS rack quad locker. As shown in Figure 1, the system includes two subsystems: the Processing Subsystem and the Support Equipment Subsystem. The Processing Subsystem is where the trash is melted and compressed, water is removed, and the tile is formed. The Support Equipment Subsystem post-processes the air/water removed from the processing chamber, houses the pumps that remove the water/vapor and provide vacuum, and houses the avionics that control the processes while logging data.

The core of the Processing Subsystem is the processing chamber, a self-contained compaction system used to compress the volume of trash and remove the water for reclamation. The 16-inch square chamber was originally sized to process approximately 11 kg of trash per day, based on a generation rate of 1.83 kg/crew member/day for up to six crew members. The chamber was originally designed to be operated three times per 24-hour period. The basic compaction operation of the chamber is driven by a piston that is actuated by a pneumatic bellows. The differential pressure across the piston, between the positive air pressure in the pneumatic bellows and the vacuum pressure in the chamber, produces the compaction forces to compress the waste.

The interior of the processing chamber, including the door, is coated with a nonstick, mold-release coating to ensure the product tile has low adhesion to the walls and can be easily removed by an astronaut in microgravity. Heaters, integrated on the back-side of the piston, are used to provide the mechanism to sufficiently raise the temperature inside the chamber to thoroughly vaporize the water for removal and melt the trash during the processing cycle. During testing and checkout it was determined that heaters were also needed on the door of the chamber to thoroughly heat the trash from both sides, and the door heaters were added prior to delivery of the system to NASA. Vapor exhaust ports are integrated on the inside of the door, and are used to evacuate the vapor from the chamber.

The Support Equipment Subsystem is also sized to reside within an EXPRESS rack double locker, adjacent to the Processing Subsystem. The additional components required to support the PMWC processing are contained within the Support Equipment Subsystem. In addition to power provisions and data acquisition, components include the condenser, gas/liquid separator (GLS), vacuum pump, and other elements to support the extraction of water from the chamber.

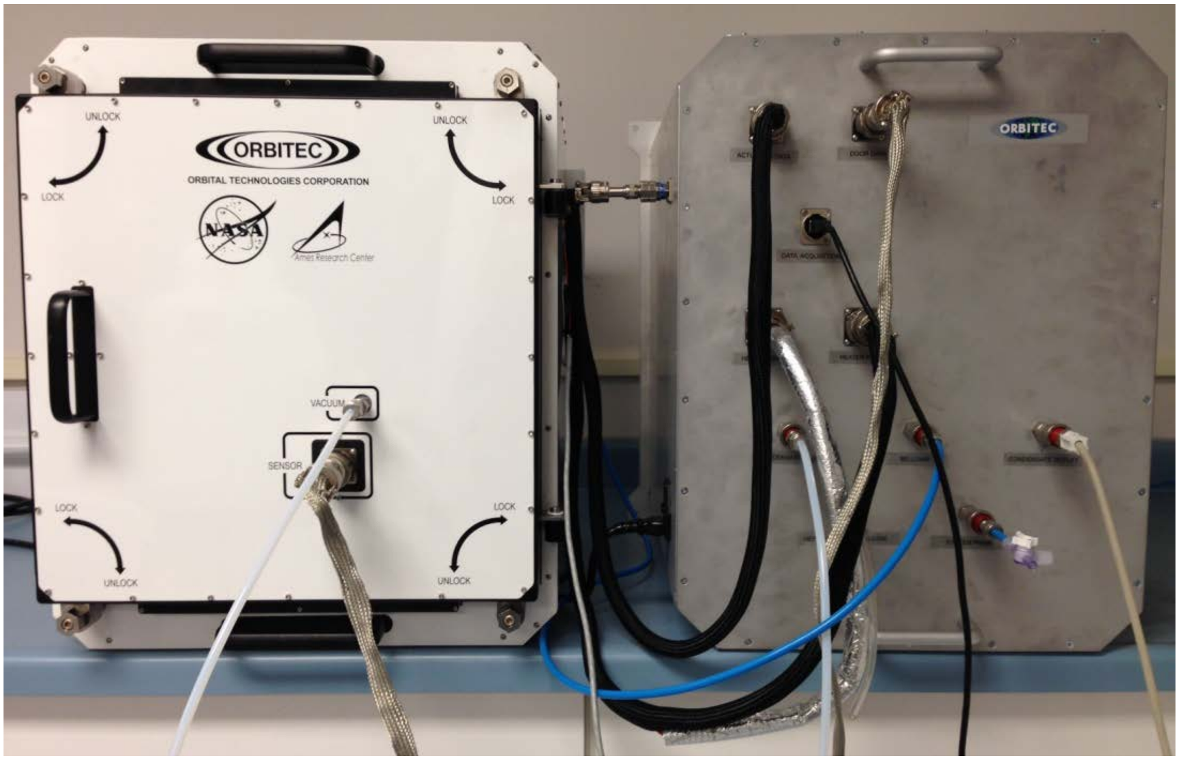

Figure 1. PMWC Prototype System: Processing Subsystem (Left); Support Equipment Subsystem (right)

B. PMWC Evaluations

Testing was conducted to evaluate performance of the system following completion of fabrication, assembly, and integration of the prototype PMWC. Details of this testing is documented in a 2015 ICES paper[6], with a top-level summary included in this paper for reference. The primary purpose of the testing was to evaluate the overall functionality of the PMWC to perform trash compaction and recover water from the waste. Data was gathered to quantify the PMWC ability to recover water and to estimate volumetric trash reduction. The different runs included variations in the trash models, melt temperatures, bellow pressures, waste mass, and cycle times. Several key performance metrics were computed for each of the test runs, including moisture recovery, specific power, specific energy consumed, and volume reduction.

Moisture recovery (%) accounted for the volume of condensate captured during each trial as a percentage of the total amount of moisture from the trash expected. The expected moisture was computed for each ersatz variation by performing independent tests to dry each of the ersatz constituents and measuring the moisture content removed by comparing the weight before and after the drying process. Specific power (W/kg) was the real time electrical power consumed by the PMWC during each trial. The specific power was calculated by data logging the supply voltage and current drawn by the system in real time, multiplying these values together, averaging the values over the time of the trial, and dividing the average by the initial mass of the waste. Specific energy consumed (kW-hr/kg) was the real time electrical energy consumed by the PMWC during each trial. The specific energy consumed was calculated by multiplying the real time power data by the interval of time over which the power was consumed, adding all of these values together over the length of each trial, and dividing the average by the initial mass of the waste. Volume reduction (%) was the percent difference calculation of the final trash volume to the original volume of trash placed in the processing chamber.

Data was recorded from each of the tests and assembled in test logs for computation of key performance metrics. Following each set of tests, testing parameters were adjusted for subsequent tests based on lessons learned from the previous testing. The general test procedure consisted of prepping the trash ersatz, loading the chamber, running the compaction and heating cycle, and removing the cooled tile when complete. An example of the resulting data for the chamber pressure, door temperature, and moisture recovery for a trial run is shown in Figure 2. This plot shows the relationship between these parameters as the process of heat melt compaction transpires. The effects on these parameters as the process progresses are described in Table 1.

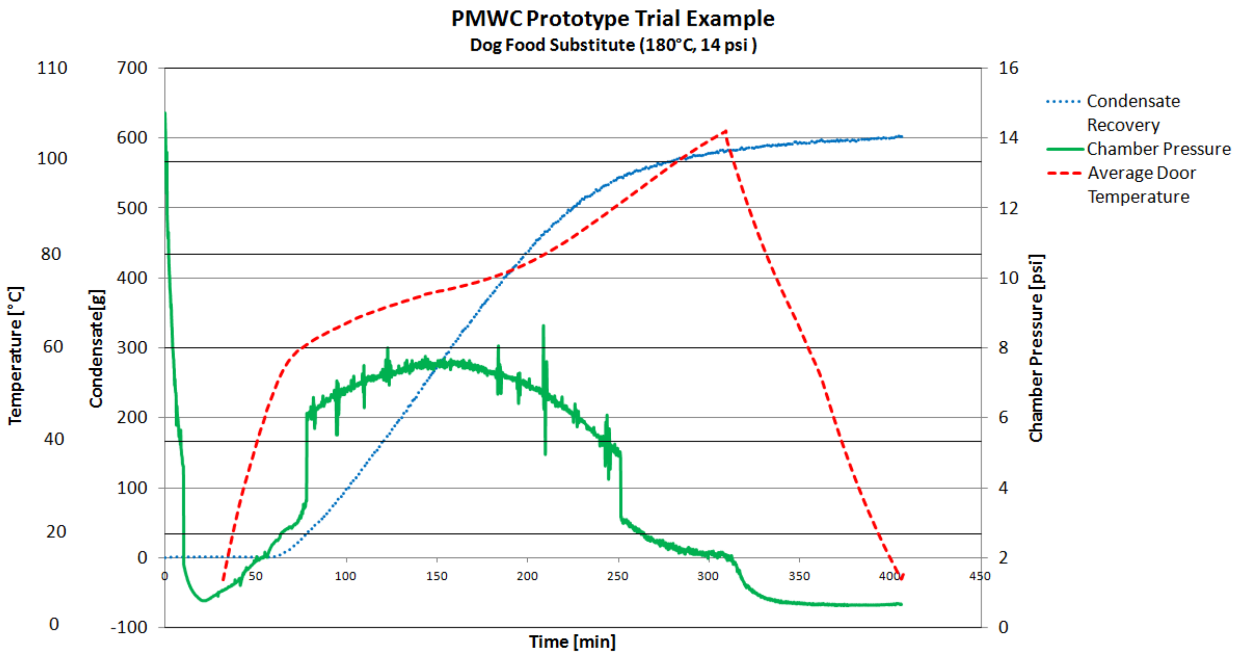

Figure 2. Data Showing Relationship of Chamber Pressure, Door Temperature, and Moisture Recovery

Table 1. Description of Chamber Pressure, Door Temperature, and Moisture Recovery Relationship

Zone	Period [min]	Chamber Pressure	Door Temperature	Condensate Collection
1	0-25	Initial depressurization to <2 psi	No change in temperature, heaters off	No collection during depressurization
2	25-75	Pressurization due to sensible heating	Sensible heating, temperature increases	No collection until boiling point of water is reached at given chamber pressure
3	75-250	Pressurization due to partial pressure of boiling and venting water vapor	Latent heat required for boiling water vapor slows temperature increase	Boiling point is reached, phase change from liquid water to water vapor occurs, consistent water collection of ≈3.5ml/min
4	250-315	Depressurization due to no partial pressure of water vapor, all water collected	Phase change concluded due to lack of available moisture, sensible heating increases temperature	Collection slows as no more water vapor is leaving the chamber, collection from residual liquid left in downstream plumbing
5	315-410	Depressurization due to sensible cooling	Sensible cooling, temperature decreases	Minimal collection of residual liquid during cooling

Overall more than 100 official test compaction runs (and double that for unofficial and/or troubleshooting) were conducted with the PMWC prototype using various trash models. The general operation of the system was relatively simple and the waste processing worked well. The non-stick surface treatment on the interior walls of the melt chamber held up extremely well, and the trash tiles came out easy and clean; the tiles were strong and sturdy. An overall summary of the key performance metrics from the testing is shown in Table 2. Excellent water recovery was demonstrated, with an overall average exceeding 93%. Volume reduction of over 75% was achieved on average. While power and energy consumption needs were reasonable, heat loss is an aspect that needs improvement.

Table 2. Testing Results Summary of Average Key Performance Metrics

	Moisture Recovery (%)	Specific Power (W/kg)	Specific Energy Consumed (kW-hr/kg)	Volume Reduction (%)
Initial System Checkout & Test (various trash models used)	98.4%	320	1.84	80.5%
Standardized Cycle Time for LRR Trash Model Ersatz Variants	100.5%*	233	1.49	68.9%
Testing with ARC Trash Model Ersatz	82.9%	214	1.53	73.7%
Application of Door Heating (ARC Trash Model Ersatz)	94.2%	218	1.31	81.7%
Overall:	**93.1%**	**255**	**1.61**	**75.3%**

*Moisture recovery >100% due to inaccuracies with theoretical ersatz moisture content as well as variability of residual condensate that remained within the PMWC system from trial to trial

C. Trash Packaging

PMWC testing and evaluations demonstrated the importance of packaging the trash as part of the processing for heat melt compaction. The way in which the ersatz is packaged has a great effect on the water recovery performance of the system. Ersatz packaging should take into account a means to allow the water to escape while still encapsulating the trash. Testing of the PMWC prototype has proven the recovery of a high percentage of the water as long as it is allowed to escape. Plastic content is also important. It was noted that without sufficient plastic content, large "holes" develop in the tiles, which would not be desirable for radiation protection.

An alternative means for trash packaging is the use of permeable trash bags. MMI is developing such a technique to encapsulate trash as part of an SBIR Phase II contract[7]. The MMI permeable trash bag is provided to store unprocessed trash and other wastes. The bags are designed to be compatible with operation of the HMC such that water vapor is allowed to escape without disintegrating the bag. The dry waste remains encapsulated during the heat melt compaction process. Additionally, antimicrobial nanometal oxides incorporated into the permeable trash bag are designed to protect the resulting HMC processed tiles against microorganism growth, allowing them to be stored safely during long-duration space missions.

The proof-of-concept for use of the permeable trash bag with the HMC application has been demonstrated. An initial SBIR effort resulted in the successful fabrication of the permeable trash bag using microporous polymer composite membranes. Its application was evaluated for water removal and recovery under low pressure and relatively low temperature without disintegrating the storage container. The encapsulation of solid waste by the permeable trash bag after the HMC process was also demonstrated. Additionally, preliminary studies on the antimicrobial property of waste disposal bags showed that silver doped CuO (Ag-CuO) provided protection against microbial growth.

III. HMC Test Unit

The current phase of development for the permeable trash bags requires further testing of the bags in the HMC application. To support accomplishment of that task, test hardware was needed to evaluate the removal and recovery of water vapor followed by the compaction and encapsulation of the trash in the permeable trash bag. Based on the previous work performed by SNC on development and application testing of the PMWC, MMI chose to have SNC implement a streamlined version of their technology to develop a HMC Test Unit that would provide the capability to test application of the permeable trash bag with the HMC process.

A. Integrated Design

Components of the HMC Test Unit include the processing chamber with a removable door, support equipment housed in an enclosure, and an external vacuum pump, as shown in Figure 3. Design efforts for the HMC Test Unit focused on developing an updated design for the processing chamber. Leveraging knowledge from the previous design of the PMWC chamber, a similar approach was taken for design of the HMC Test Unit. A bellows is used to apply pressure to a piston that compresses the trash inside the chamber. Heaters are incorporated on the piston as well as the door to provide even heating from both sides. The door was designed to be removable so trash could more easily be loaded into the chamber for tests, and so the tile could be easily removed following processing.

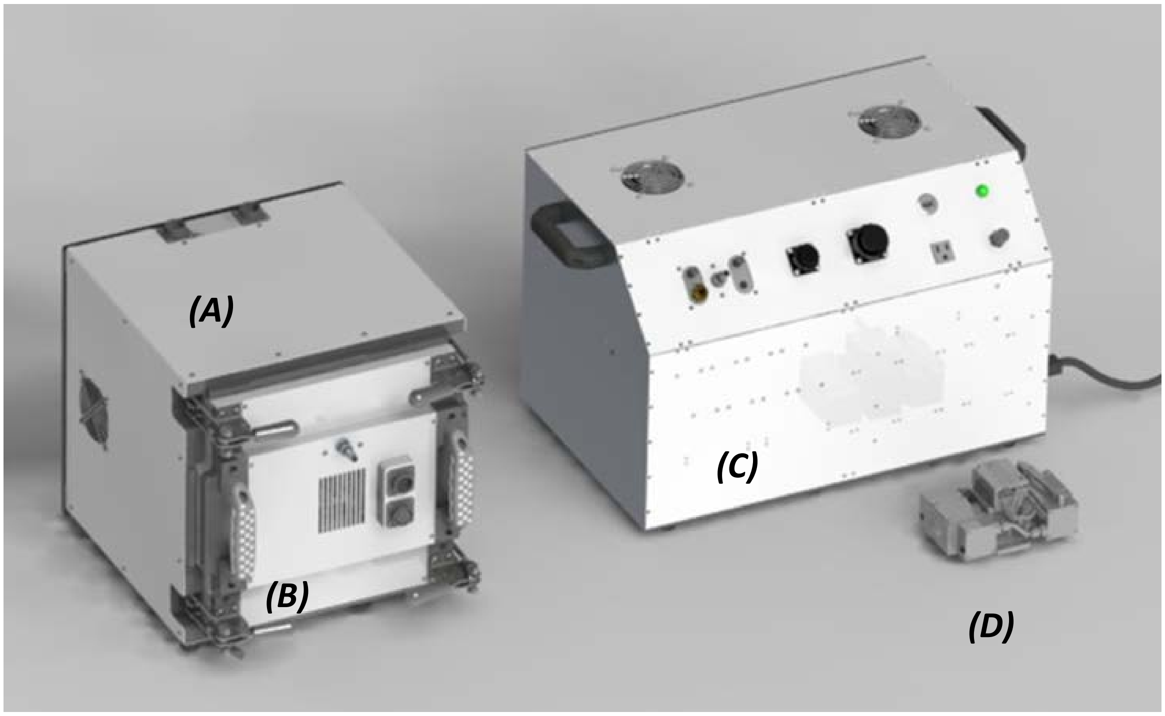

Figure 3. HMC Test Unit Comprises: (A) Processing Chamber; (B) Removable Door; (C); Support Equipment; and (D) Vacuum Pump

The size of the chamber was determined through discussions with NASA JSC and NASA ARC personnel. While the PMWC chamber accommodated 16-inch square tiles to evaluate maximum capacity for the ISS EXPRESS rack, the NASA ARC GEN2 is sized for 9-inch square tiles. The square shape for the tiles was determined based on packing efficiencies, as well as being a good shape to use for potential radiation shielding. Chamber size for the HMC Test Unit also included considerations for bellows sizing as well as the goal to accommodate trash processing two times per day for four crew members. Taking all aspects into account, the chamber dimensions were sized to accommodate an 11.5-inch square tile. Depth of the chamber allows up to eight inches for trash loading. The interior of the processing chamber, including the door, was coated with a nonstick, mold-release coating to ensure the product tile has low adhesion to the walls and can be easily removed.

The support equipment was designed to be housed in an enclosure separate from the processing chamber. These additional components include power provisions, data acquisition and controls, bellows pump, and associated plumbing for the removal of water vapor from the chamber. The vacuum pump, provided separately by MMI, was positioned externally from the enclosures.

A hardware schematic for the HMC Test Unit is shown in Figure 4. The processing chamber includes the bellows used to apply pressure to the piston to compress the trash against the door. Heaters are shown on both the piston and door sides to apply heat along with the compaction force applied to the trash during processing. The support equipment enclosure includes the power supply, data acquisition, heater and relay controls, and signal processing. The bellows compressor, associated valves, and sensors are also included in the support equipment enclosure, but the vacuum pump and controls are positioned externally.

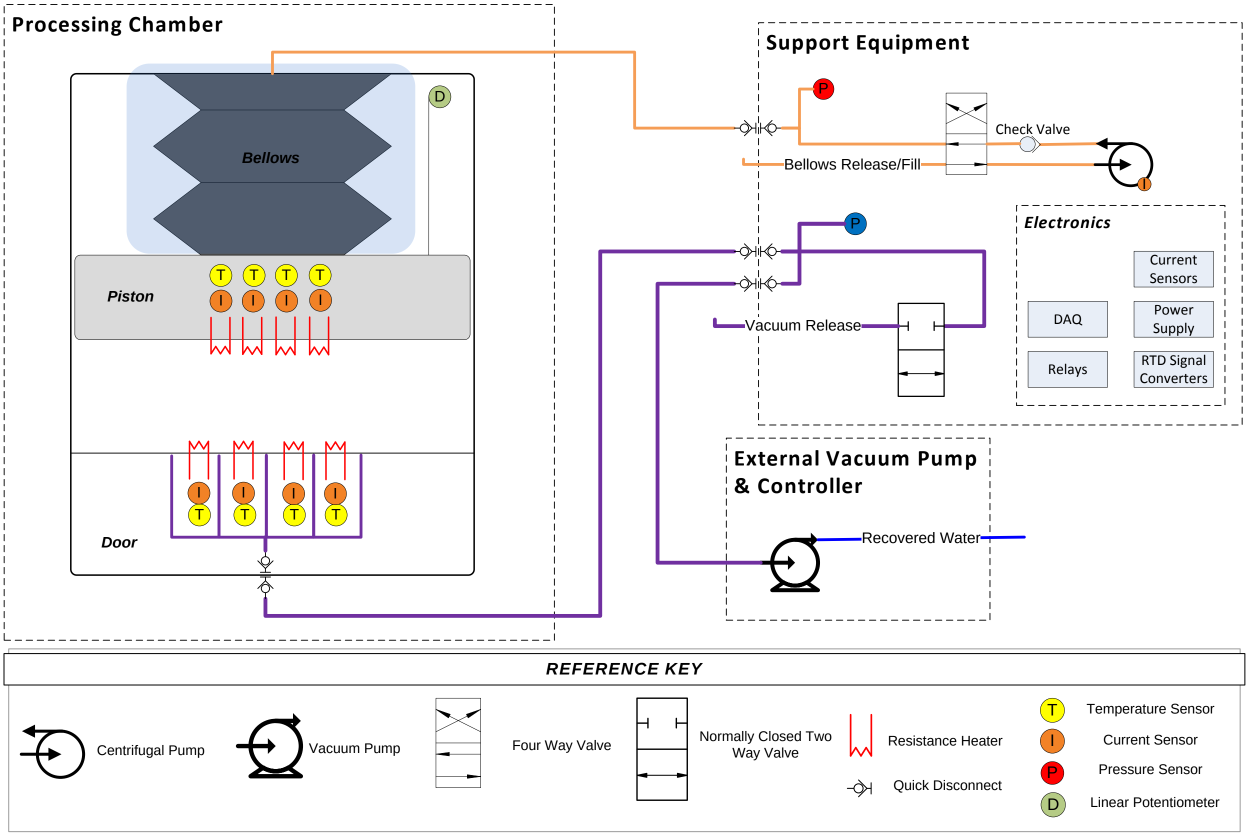

Figure 4. HMC Test Unit Schematic

Following the design, components were fabricated and assembled. The processing chamber is shown in Figure 5. In the left side of the figure the inside of the chamber is visible with the door off. The right side of the figure shows the chamber with the door locked in place. The chamber door and its associated vapor ports are shown in Figure 6. Figure 7 shows the support equipment enclosure.

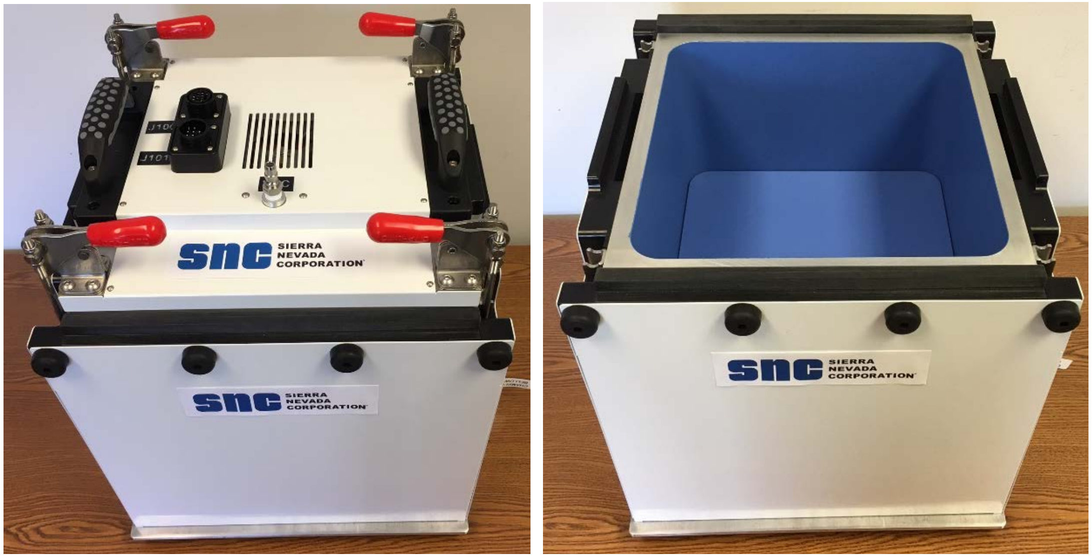

Figure 5. Processing Chamber with Door On (left) and Door Off (right)

Figure 6. Chamber Door Interior Face with Vapor Ports

Figure 7. Support Equipment Enclosure

B. Processing Operations

Implementation of the permeable trash bags requires a two-step process for heat melt compaction, decoupling the evaporation and consolidation stages. First, the water content must be evaporated with a minimal level of temperature and consolidation pressure in order to maintain the porosity and physical integrity of the waste containing permeable trash bags. After the water content has been reduced by 90-95%, the temperature can be increased in conjunction with the final compaction pressure being applied.

While the exact effect of the process conditions during the evaporation-to-consolidation process transition time is indeterminate, it is not expected to negatively impact the overall process functionality. Following delivery of the HMC Test Unit to MMI, trials will be run to determine the optimal processing parameters for each part of the process. Initially, based on current knowledge of the permeable trash bags, evaluations will consist of the following steps:

- Evaporation process
    - Adjust temperature set point between 70 ºC to 80 ºC
    - Set vacuum level between 200 to 300 mbar
    - Set bellows compressor to minimum pressure that matches up to the vacuum level
    - Start evaporation process and monitor water extraction to the 90% to 95% point
- Consolidation process
    - Adjust temperature set point between 150 ºC to 180 ºC
    - Set vacuum level between 300 to 500 mbar
    - Set bellows compressor to expected compaction force
    - Start consolidation process and monitor displacement until full consolidation is achieved

C. Functional Checkout

Functional checkout of the HMC Test Unit was performed at SNC prior to delivery of the unit to MMI for application with the permeable trash bags. Checkouts were performed using both the permeable bags and a combination of plastic and cloth trash materials. The two-step evaporation and consolidation process, as described in Section II.B above, was followed during these functional checkouts to ensure the system functioned as designed and to verify the processing procedures. Trash was loaded into the processing chamber as shown in Figure 8: trash was loaded into the permeable bags which were in-turn loaded into the chamber (picture on left); the plastic trash mix was loaded directly into the chamber (picture on right). The door was locked in place and the processing was initiated to evaporate the water and consolidate the trash. Examples of resulting tiles from the HMC Test Unit are shown in Figure 9. The purpose of the functional checkout was limited to ensuring operation and functionality of the system to enable subsequent testing of the permeable trash bags; detailed performance metric data was not gathered.

Figure 8. Loaded Trash in Processing Chamber, showing Permeable Bag (left) and Plastic Trash Mix (right)

Figure 9. Resulting HMC Tile, showing Permeable Bag (left) and Plastic Trash Mix (right)

IV. Conclusions

The HMC Test Unit was designed and built to facilitate testing of permeable trash bags. The HMC Test Unit leverages the design from previous developmental models to assemble a streamlined version focused on evaluation of the permeable bags to evaporate the water vapor followed by encasement of the trash during compaction. The unit is sized to accommodate an 11.5-inch square tile, somewhat larger than the 9-inch square tiles processed using the NASA ARC GEN2 HMC and smaller than the 16-inch square tiles processed using the SNC PMWC. Following design, fabrication, and checkout, the unit will be delivered for testing the application of permeable bags for the heat melt compaction process.

Acknowledgments

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