Technical Risks Associated with Heat Melt Compaction Systems

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The processing of trash and waste is a welcome and valuable addition to humans living and working in space. Besides the obvious desire to have a pleasant and productive habitation environment, trash management has many practical benefits for crew health, resource recovery, and volume reclamation through garbage compaction. The Trash Compaction and Processing System (TCPS), which is a NASA project to develop a trash processing system for long-duration spaceflight, is currently undergoing concept development with engineering prototype validation through two contracted efforts. The development efforts are being supported with activities associated with the NASA Generation 2 Heat Melt Compactor (HMC). The HMC is a facility that compacts trash, recovers water, heats the trash to eliminate biological activity, and manages gas and vapor effluents. The resulting residual processed trash is a compact tile that is free of biological growth and that can be used for augmenting radiation shields. The work being conducted with the HMC focuses on high risk technical areas with respect to operations, subsystem performance, and ISS effluent management interface requirements. This paper gives an overview of the technical risks and the current use of the HMC as a facility for reducing risk.

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Nomenclature

AdWRS = Adsorbent Water Recovery System
AES = Advanced Exploration Systems
ARC = Ames Research Center
a_w = water activity
ECLSS = Environmental Control and Life Support Systems
EXPRESS= EXpedite the PRocessing of Experiments to the Space Station
FTIR = Fourier-transform infrared spectroscopy
GBT = Gunk Buildup Test
GCMS = gas chromatography-mass spectroscopy
Gen 1 = 1st Generation HMC
Gen 2 = 2nd Generation HMC
GRC = Glenn Research Center
GWT = gas and water test
HMC = Heat Melt Compactor
ISS = International Space Station
JSC = Johnson Space Center
LEO = Low Earth Orbit
LR = Logistics Reduction
MMI = Materials Modification Inc.
MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration
NextSTEP= Next Space Technologies for Exploration Program
psia = pounds per square inch, absolute
RFP = request for proposal
SBIR = Small Business Innovation Research
SCCS = Source Contaminant Control System
SMAC = Spacecraft Maximum Allowable Concentration
SNC = Sierra Nevada Corporation
TCPS = Trash Compaction and Processing System
TGA = thermogravimetric analysis
TOC = total organic carbon
VES = Vacuum Exhaust System
WSTF = White Sands Test Facility

I. Introduction

THE need for trash and waste management is being pursued through the NASA's Logistics Reduction (LR) project under the Advanced Exploration Systems (AES) Habitat Systems program. As identified by the Decadal report and previously specified by the 2015 NASA technology roadmap[1] and reiterated with the 2020 NASA Technology Taxonomy, TX06.1.3, Waste Management,[2] "Waste management provides for safe collection, processing, resource recovery, and volumetrically efficient storage of waste" with identified examples of "Trash volume reduction and stabilization," "Long duration trash storage," and "Trash/waste removal systems."

A contracted effort is currently in progress to develop a Trash Compaction and Processing System (TCPS) under the Next Space Technologies for Exploration Partnerships (NextSTEP) program. NextSTEP is a cooperative public-private approach for achieving strategic goals for human space exploration through the combined efforts of government, industry, and universities. In 2018, NextSTEP Appendix F: Logistics Reduction in Space by Trash Compaction and Processing System (TCPS)[3] was released to develop a trash processing system as an International Space Station (ISS) technology demonstration with the goal of advancing trash management for future long duration missions.

The TCPS project, as dictated by the NextSTEP cooperative approach, involves NASA public and industry private cooperation. For the private effort, two contracted efforts were awarded in 2019 and continue today. Collins Aerospace and Sierra Nevada Corporation (SNC) were selected to independently develop separate TCPS concepts that include hardware prototyping, operational demonstrations, and validation of operational concepts. For the public effort, NASA is conducting risk reduction activities that include both technical hardware development and tests, and operational methods. The intent of this approach is to open up the problem space to new and un-explored industry inspired solutions and not be restricted by NASA's own internal research and development work; but at the same time NASA willingly shares what it has learned from its own efforts. This gives industry a "running start" towards an eventual well-defined, understood, and validated TCPS concept that will lead to a follow-on ISS flight demonstration.

II. Trash Compaction & Processing System Description

NASA has explored TCPS technology through the development of the Heat Melt Compactor (HMC). An extensive list of published HMC work is listed in Attachment 3 in Section 7.3 of the NextSTEP Appendix F Solicitation.[4] NASA's work with the HMC has resulted in a set of primary functions that are characteristic of a TCPS designed for long duration space missions as illustrated in the use case diagram of Figure 1. The functions required of a TCPS are: "to reduce trash volume into a form suitable for safe and efficient long duration storage; to safen[i] the trash to reduce the risk of biological activity; to stabilize[ii] the trash physically, geometrically, and biologically (biologically inert); and to manage the effluents that can be expected to come off the trash during processing. These effluents need to be compatible either with the ECLSS air and water life support systems if vented into the crew cabin, or compatible with a vacuum exhaust venting system if vented to space vacuum. Expected effluents are aqueous solutions with contaminants, organic and inorganic gases, water vapor, and entrained particulates.

- **Reduce volume** to a suitable form for efficient long-endurance storage
- **Safen** to eliminate and/or reduce the risk of biological activity
- **Stabilize** physically, geometrically, and biologically
- **Manage effluents** gaseous, aqueous, and particulates that evolve from processing

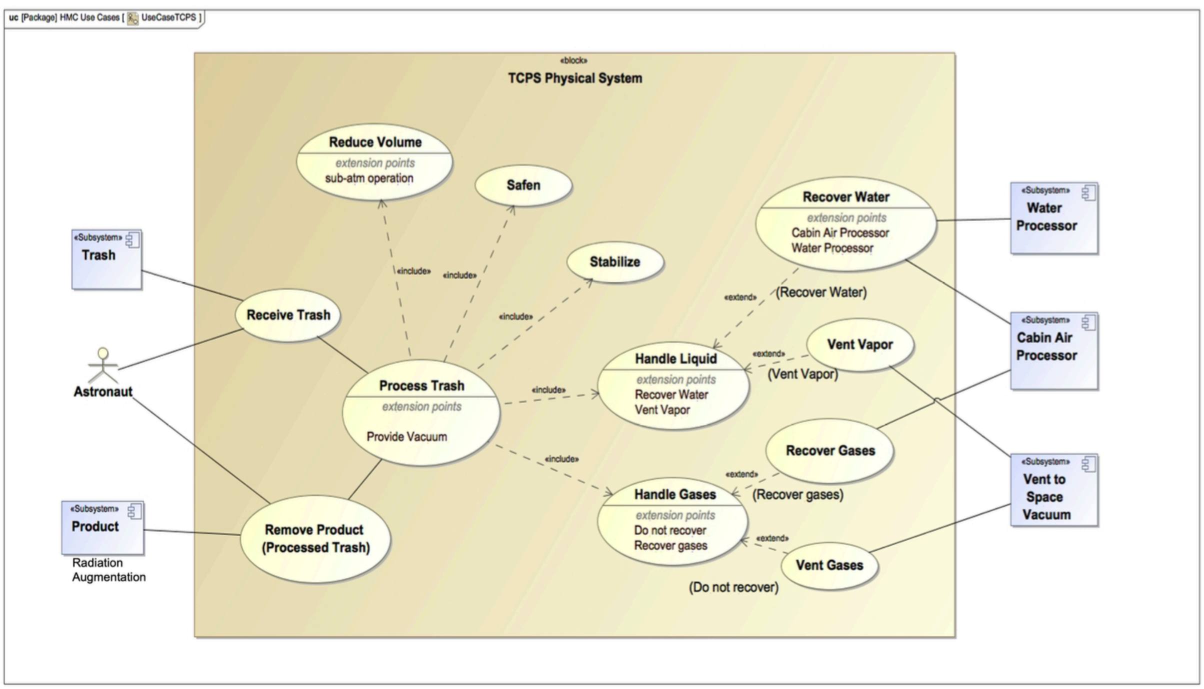

Figure 1. Trash processing use case diagram for long-endurance space missions; Requirements are to reduce trash volume, safen the trash, stabilize the residual product, and manage the effluents.

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[i] Safen is defined as controlling hazards with sufficient certainty to be considered safe for human operations.

[ii] Stabilize is defined as making the product unlikely to change from its final form.

To address these requirements the HMC Generation 2 (Gen 2) serves as a test bed to test various technical approaches with performance verification and operational validation. The basic operation of an HMC trash processor[5] is to mechanically compact the trash, heat the system, drive off and capture the water, and continue heating until plastics flow and microbiological activity ceases. Measures of performance are 400-600 kg/m^3 density of the compacted trash tile, tile water activity of $a_w < 0.6$, and high tile robustness with no flaking, crumbling, or dusting, etc. Water recovery at a low boiling point temperature is enhanced through the use of vacuum. Safening is accomplished through a combination of heat applied to the trash at temperatures up to 160 °C to melt plastics and kill microbes. Stabilization is accomplished during the higher temperature operation to melt plastics; upon cooling the residual tile product retains a compressed rigid form. Effluent water vapor is condensed and collected downstream, which for a spaceflight system, would require a liquid/vapor phase separator that can operate in zero gravity. Volatile organic and inorganic gases can be processed using an oxidation contaminant control system to meet Spacecraft Maximum Acceptable Concentrations (SMAC) if gases are to be released into the cabin, or the gases and water vapor can be directly vented to space vacuum through the Vacuum Exhaust System (VES), if requirements are met. Constraints on releasing to the VES are maximum temperature (< 45 °C), dewpoint temperature (< 15.5 °C), mass flow, and non-corrosive gases. Fire safety needs to be considered. The flammability limits of combustible gases confined within trapped spaces and conditions for auto-ignition and ignition sources need to be examined. The flammability of the residual tile also needs to be understood. Tile robustness while being removed and stored is also important. Noxious gases and particulates escaping when removing the residual tile need to be considered, along with tile handling and tile off-gassing during storage. Another challenge is dealing with precipitants and particulates, such as salts, that may precipitate from expulsed water and condensable organic gases that collect as "gunk" in vent ports and downstream plumbing over many trash-processing cycles; and accumulated gunk that can breakaway and be entrained with flowing gases to downstream systems, and sliding and vacuum seals can be prone to premature failure. Reliability, maintainability, and repairability come into play for an envisioned 5-year mission lifetime. Trash processing systems need an understanding of the interdependence of different processing parameters. Parameters include vacuum vs. cabin pressure operation, applied heat and temperature control. Lower pressure allows water to boil at a lower temperature but at a lower recovered amount. Higher temperatures allow for increased water recovery of trapped water but at the expense of higher concentrations of volatile noxious gases. The use of a dry sweep gas can aid in removing water from the trash, but may require a separate additional dehumidification recirculating gas subsystem. But without a sweep gas, the transport rate of water vapor in a stagnant gas - such as for trash drying under a less than absolute vacuum - is inversely dependent on the logarithmic mean average of the residual gas partial pressure, hence, for a binary mixture, the higher the residual gas concentration, the lower the transport rate for the water vapor.[6] Pressure safety is also important. During higher temperature operation, trapped water may suddenly boil resulting in large and sudden pressure spikes within the compaction chamber.

III. TCPS Technical Risk

The HMC Gen 2 unit is being used to support the contracted TCPS efforts. The HMC is also being used to independently reduce technical risks. Major risk reduction work includes: condensed effluent hydrocarbon buildup on downstream systems; catalytic oxidation of effluents; non-stick processing chamber coatings; biological growth on residual dry tiles; tile flammability; tile robustness to quantify breaking, crumbling, or flaking when handling; recovered water total organic carbon (TOC) and ion analysis; and effluent gas analysis using gas chromatography-mass spectrometry (GCMS), Fourier-transform infrared (FTIR), and thermogravimetric analysis (TGA) when processing individual trash components[11] and representative model trash for determining compatibility with ISS SMAC, ISS VES for venting to space, and Environmental Control and Life Support Systems (ECLSS) water requirements.

An examination was conducted in December 2019 of the status of TCPS technology development. This included the work of NASA Ames Research Center (ARC), TCPS contractor design concepts to date, TCPS requirements as described in the NextSTEP request for proposal (RFP), and the previously described risk considerations. Table 1 lists the identified technical risks. Fifteen risks - two red, nine yellow, and four green - are prioritized according to the standard 5x5 likelihood times consequence product. The risks in Table 1 are categorized into functional purpose. These are trash processing, safening, stability, effluent management (gas, water vapor, and liquid water), reliability, and safety (programmatic risks were not considered in this technical effort). Risk are prioritized according to LxC product in the righthand column. The major identified risks are water separation in microgravity, trash biological safening (particularly of the stored residual tile), gunk build-up after repeated operations without cleaning or maintenance, an analysis of the gaseous effluents with an evaluation of their compatibility with ECLSS air and water systems, and SMAC, and VES compatibility. Following are detailed descriptions of the higher priority risks.

Table 1. Summary Risk Reduction List.

Summary Risk List (15 risks, 2 red, 9 yellow)

Risk ID #	Functional Category	Risk Title	Risk Statement	Risk Type	Likelihood	Consequence	L X C
6	Manage water effluent	Water Separation in Micro-G	If water (that contains solutes and particulates) cannot be sufficiently separated from the effluent, then water cannot be collected and VES interface requirements may not be achieved.	Technical	4	4	16
14	Safening	Trash Biological Safening	If the trash is not properly safened and kept safe, then microbes may grow resulting in concerns for crew health.	Hazard	3	5	15
9	Process Trash	Gunk build-up causing difficult tile removal, compaction jams, vent plugging, seal compromise	If gunk builds up in the TCPS then trash tiles may stick and be difficult to remove or jams may occur during compaction, or water vapor and gases may not exit if vent ports are plugged, or (sliding) seals may be compromised.	Technical	4	3	12
10	Reliability	TCPS breaks down or procedures are mis-interpreted	If the TCPS does not work due to break down or maintenance issues or mis-interpretation of procedures, then trash processing may not be accomplished	Technical	3	4	12
1	Manage gaseous effluents	Contaminant Sources not contained, gas leak during operation, or gasses released when removing tile.	If hazardous or noxious gas contaminants produced during the TCPS process leak into the crew cabin, or are released when removing the processed tile, then crew health and safety may be put at risk.	Hazard	2	5	10
17	Process Trash	Operational Scenarios	if proposed operational scenarios are not validated, then there is a chance that they will not work as expected in space	Technical	3	3	9
2	Manage effluents	Pressure Control and Flow Rate into VES	If effluent flow, thermodynamic conditions, and compound type cannot meet ISS VES requirements, then venting to space vacuum may not be possible	Technical	3	3	9
16	Manage gaseous effluents	CatOx required for venting to cabin (SCCS)	If catatytic oxidation of effluent gases is not effective, then venting to cabin (or VES) may not be an option	Hazard	3	3	9
3	Manage gaseous effluents	Tile Off-Gassing and odors	If off-gassing from the tiles is not understood then there is possiblity that toxicology will not allow tile storage on ISS.	Technical	3	3	9
4	Safety	Flammable Event	If combustible gases collect in the TCPS then there is a possibility of a flammable event	Hazard	2	4	8
7	Stabilize	Stabilize Trash	If the tile is not physically stable (crumbles, breaks, flakes), then particles may escape into the cabin and present a safety concern to the crew.	Hazard	4	2	8
19	Safety	Tile Flammability	If tiles do not meet safety flammabiliy requirements, then tiles cannot be stored in the open cabin and secondary flight objective to test for microbio growth on the tiles in the cabin environment will not be possible.	Technical	3	2	6
5	Safety	Sudden Pressure Rise	If a sudden rise in pressure in the TCPS occurs (such as if flashing of water into vapor) and steam leaks from the system, then crew safety is a risk.	Hazard	1	5	5
13	Manage effluents	Gas and water sample analysis	If there isn't a process and standard procedure for analyzing gas and water samples from TCPS vendors and ISS TD return samples, then performance of TCPS effluent processing will not be quantified	Technical	1	4	4
12	Safety	Noise Limit	If TCPS components are too noisy, then safety hazard requirements may not be met	Hazard	1	2	2

A. Risk Reduction Plan

Maximizing the risk reduction efforts through the HMC facility, the notional Risk Reduction plan shown in Figure 2 is used for testing and scheduling guidance. Four technical testing areas are shown in

Figure 2 as horizontal swim lanes. Each technical area addresses corresponding risk ID numbers of Table 1. Vertical lines indicate the period of performance. Activities within the swim lanes are labeled – these are the actual test activities and test campaigns resulting in recorded data, system performance measures, and observations. Dashed lines indicate dependencies between functional areas, between test activities, and between functional areas and test activities.

1. GWT Analysis / SCCS

The first risk reduction campaign is shown in the first horizonal swim lane and is titled GWT Analysis / SCCS. This effort addresses areas of trash processing including determining the effluent gas composition, tile quality, tile safening, and operational scenario. For this test campaign, 16 separate HMC trash processing runs were conducted in a tightly controlled fashion to measure effluent gas composition, water quality, tile water activity, tile offgassing, and tile biological (in)activity, for three standard types of trash, with and without semi-permeable water vapor containment bags developed by Materials Modification Inc. (MMI) under a Phase III Small Business Innovation Research (SBIR)[7].

Controls set in place are baseline effluent measures and flushing the HMC between each tile. Results of this campaign are reported elsewhere.[8]

2. AdWRS

The second risk reduction campaign shown in swim lane two is titled Adsorption Water Recovery System (AdWRS). This test effort will examine the adsorbent water recovery system both at laboratory bench scale and EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) rack flight system prototype. Details of the flight prototype are reported elsewhere.[9]

3. GBT / SCCS

The third campaign is titled Gunk Buildup Test (GBT) / Source Contaminant Control System (SCCS). This effort will examine how gunk builds up within the trash processing system over repeated cyclical operation without intermittent cleaning. This effort includes testing and evaluation of non-stick coatings, and evaluation of water vapor permeable MMI containment bags. This effort also includes evaluating the effectiveness of the SCCS that uses a catalytic oxidizer and a carbon bed pre-filter.

4. VES Simulator and Multi-component Phase Equilibria

The last test effort is examining and demonstrating the control of gaseous and water vapor flow conditions to a VES simulator. The VES simulator is a long glass tube with a pressure regulating value between the VES and TCPS. Water vapor and gas mixtures will be throttled across the value at different thermodynamic state conditions to verify phase equilibria and whether condensation occurs or does not occur as predicted.

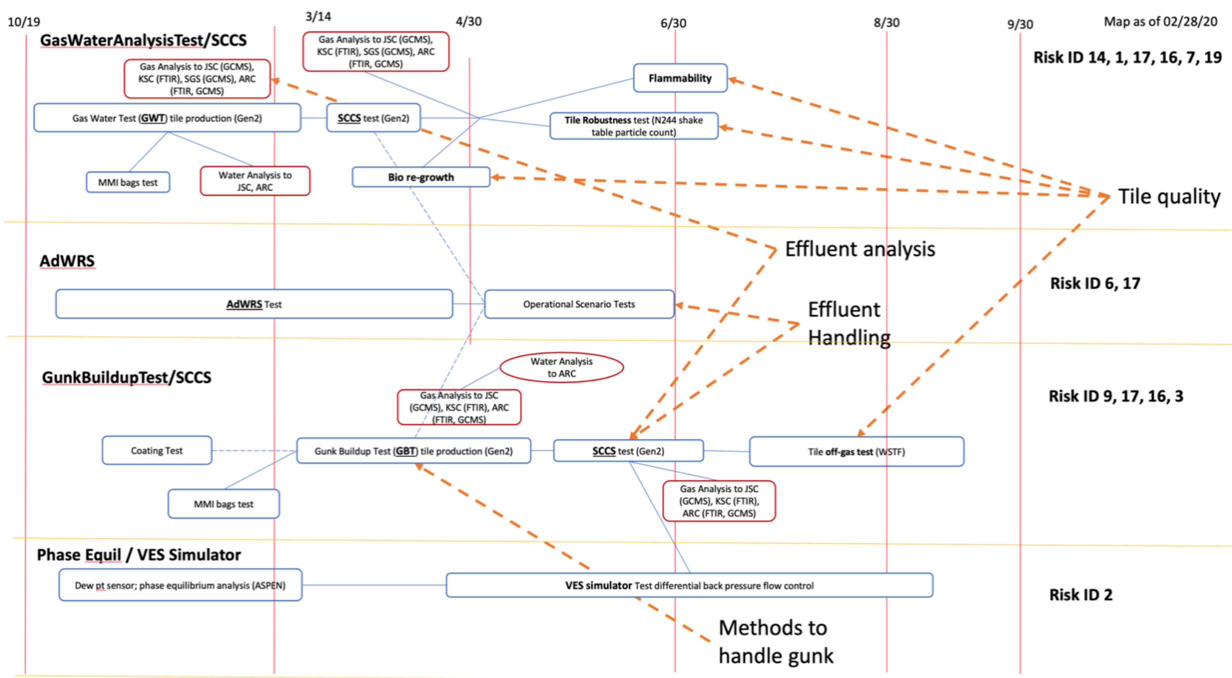

Figure 2. Risk Reduction Campaigns and Mitigation Activities corresponding to identified risks in Table 1.

B. Risk Description and Mitigation

1. Risk ID #6: Water Separation in Microgravity

"If water (that contains solutes and particulates) cannot be sufficiently separated from the effluent, then VES interface requirements may not be achieved."

When operating the TCPS it is expected that, for a given pressure, a temperature will be reached in which water vigorously boils and is released as wet steam from the trash. This is the most efficient way to release water from the trash, however, wet steam is not allowed into the VES when venting. It is also desirable to recover this water. A system for condensing the water vapor and collecting the water from gaseous effluents is needed. HMC is exploring an AdWRS with regenerative operation that has been previously described.[10] Other methods could include centrifugal, membrane, and surface tension devices. The water recovery device will need to handle up to 200 mL of water per kg of trash that is available on average in moist trash, and it is expected that on average approximately 5 g/min of water flow over 40 minutes. In addition, if venting to space vacuum is desired, the device will need a controlled release into the VES and be able to satisfy dew point of < 15.5 °C, a maximum temperature requirement of 45 °C, and mass flow of < 30 g/min for 1st min and 5 g/min for 2nd min with a flow interruption of zero to reset the mass flow condition back to < 30 g/min for1st min and 5 g/min for 2nd min, etc. Additionally, dilution with air to reduce the dew point requires a dilution ratio of 90:1 for air:water that would not be practical and would likely violate the mass flow requirement.

2. *Risk ID #14: Trash Biological Safening*

"If the trash is not properly safened and kept safe, then microbes may grow resulting in concerns for crew health."

When the tile is removed after TCPS processing, a water activity, $a_w < 0.6$ is required to retard microbial growth.[11] Though this may be accomplished at the end the processing cycle and at removal of the tile, a violation of $a_w < 0.6$ may be possible if the tile is in storage and left to cabin environment. This could possibly occur if the tile (or a section or spot of the tile) is rewetted, or if it is stored in a high humidity "corner" of the cabin. Previous HMC tests indicate that there is no biological growth when trash is processed at 180 °C for 1 hour or 150 °C for 3 hours. However, longer term test when stored under humid conditions have not yet been conducted. Plans for such testing are being developed. In addition, semi-permeable trash processing bags with anti-growth coatings developed by MMI under a SBIR effort will be tested for re-growth inhibition.

3. *Risk ID #9: Gunk buildup causing difficult tile removal, compaction jams, or vent plugging*

"If gunk builds up in the TCPS then trash tile may stick and be difficult to remove, or jams may occur during compaction, or water vapor and gases may not exit if vent ports are plugged, or seals may be compromised."

Operations with HMC Gen 1 and Gen 2 have shown that considerable gunk buildup occurs during repeated trash cycle processing, resulting in degraded performance and difficulty to remove tiles. Vent ports and downstream effluent lines have also shown to collect condensable oils and can become obstructed and plugged. Access doors are hard to open and compactor movement may become difficult. This can be become a significant problem when repeated operation is required without intermittent cleaning. To address this issue, HMC is being run continuously to determine how, where, and to what degree gunk buildup is occurring. In addition, non-stick coatings are being assessed to determine ways to reduce time for cleaning and maintenance in removing gunk.

4. *Risk ID #1: Contaminant Sources not contained, gas leak during operation, or gases released when removing tile*

"If hazardous or noxious gas contaminant produced during the TCPS process leak into the crew cabin, or are released when removing the processed tile, then crew health and safety may be at risk."

Processing trash at elevated temperature releases undesirable gaseous compounds. Depending on the process temperature and concentrations, any release into the crew cabin, such as from a leak during operation or upon opening the door when removing a cool tile could violate SMAC. Operating the trash process under vacuum can reduce or eliminate leaks from the TCPS. To understand the gaseous effluents that occur during processing, ARC conducted a vigorous tile making and effluent collection and analysis campaign. Sixteen trash batches have been processed under controlled conditions with the collection of water and gas samples. The sampling included three types of trash models ranging from a high cloth model, to a nominal model, to a high liquid model.[12] MMI bags were also tested to determine the bag effectiveness in holding back contaminants while allowing water vapor through. The gas samples were collected at different time and temperature intervals during processing. These water and gas samples were analyzed using outsourced and NASA Johnson Space Center (JSC) GCMS services and a Gasmet continuous portable FTIR system. The results for the complete test campaign are reported elsewhere.[13] Additionally, individual trash components were separately analyzed with TGA-FTIR at NASA Glenn Research Center (GRC) to identify specific gas components from specific trash components.[12] Previous component testing indicates high concentrations of carbon disulfide off-gassing from nitrile gloves.[14]

5. *Risk ID #17: Operational Scenarios*

"If proposed operational scenarios are not validated, then there is a chance that they will not work as expected."

A complete TCPS requires integration of many subsystems, and integrated testing to determine performance, with the need to validate operational scenarios for the complete system. This includes trash model type, compaction, heating, effluent management, tile removal, handling, and storage. Operational conditions include optimizing clean water recovery to minimize or eliminate the need for post processing for ECLSS systems. Understanding the various operational scenarios allows for options in contingency planning. For example, if a source contaminant control system is inoperable, can undesirable gases be vented to the VES? Can clean water be recovered at low temperature and be directly released to ECLSS. Can dirty water saturated with dissolved organics be collected and released to the VES while satisfying mass flow, temperature, and dew point constraints? ARC is addressing operational scenarios by including all expected major components for a TCPS in an integrated HMC facility that includes a VES simulator (long glass tube for visual inspection of condensables) with high capacity vacuum pump, a catalytic oxidizer for gaseous contaminant control, and an engineering flight design AdWRS for water collection. The complete system will be used to understand the trade-offs between various operational scenarios and system performance optimization.

6. Risk ID #2: Pressure and Flow rate control into the VES

"If effluent flow, thermodynamic conditions, and compound type cannot beat ISS VES requirements, then venting to space vacuum may not be possible."

Venting to space vacuum will be driven by the VES requirements. The main requirements with regard to temperature, pressure, dewpoint, and mass flow were given in risk ID #6. It is expected that the TCPS technology demonstration on ISS will be used to demonstrate venting to the VES. A means of control for flow rate and water vapor thermodynamic state into the VES is to use a simple pressure regulating valve. To first order, an examination of the pressure-enthalpy phase diagram of pure water shows that in order to not have condensation in the VES, the state conditions of water vapor upstream to the pressure regulating value (i.e., throttling valve) must be unsaturated water conditions. This can be examine with the aforementioned VES simulator. In addition, other compounds will be present in the gaseous flow stream, which constitutes complex mixtures with multicomponent phase diagrams not indicative of the pure components. ARC and JSC are looking into the phase equilibrium of multicomponent mixtures to gain a better understanding whether azeotrope maximums are of concern.

7. Risk ID #16: Catalytic Oxidation for cabin venting

"If catalytic oxidation of effluent gases is not effective, then venting to cabin (or VES) may not be an option."

A means for rendering noxious and toxic gases is needed if released of effluents for resource recovery into the crew cabin is desired. Both SNC and ARC are examining gaseous management. A catalytic oxidizer supplied by NASA Marshall Space Flight Center (MSFC) and developed by Umpqua Research Company is currently being integrated into the HMC test facility. Specifics of the system can be found elsewhere.[15]

8. Risk ID #3: Tile off-gassing and odors

"If off-gassing from the tiles is not understood, then there is a possibility that toxicology will not allow tile storage on ISS."

After trash processing and upon opening the compactor door to remove the cooled formed trash tiles, there is a definite odor that persist. This odor is evident on tiles even after sitting in storage for a period of time. Tiles may off-gas during storage with odorous smells, and the combined concentration of many stored off-gassing tiles may violate SMAC. Preliminary testing conducted at White Sands Test Facility (WSTF) between March and April of 2013 of off-gassing from HMC tiles at 120 °F in 20.9% oxygen atmosphere pressure of 11.9 psia over 72-hour time period has detected 56 compounds by GCMS with furan and dimethyl disulfide being the driving compounds for the toxic hazard index.[16]

9. Risk ID #7: Stabilize Trash

"If the tile is not physically stable (crumbles, breaks, flakes), then particles may escape into the cabin and present a safety concern to the crew."

Loosely compacted tiles resulting from low compaction pressure or trash components of different compressibility distributed unevenly may crumble or break or flake with particles escaping into the cabin when tile is removed from processing chamber. Floating particulates can be inhaled by crew members or may find residence in a high humidity location where water can be re-absorbed thus allowing microbial growth. Earlier HMC testing has indicated that > 40 psia of compaction pressure is desirable for a well-formed stable tile. Trash containment bags, such as those developed by MMI, can be used for encapsulation of the compacted trash while allow water permeation during trash processing.

10. Risk ID #4: Flammable Event

"If combustible gases collect in the TCPS then there may be a possibility of a flammable event."

It has been established that hydrocarbon gases, such as methane, pentane, and ethanol evolve from the process. These volatiles, if trapped in closed volumes and mixed with air, can become a source of concern especially if there are electrical systems and wiring or mechanical systems that could be a source for ignition. Leakage into closed trapped volumes can be a result of leaky seals or unwitting designs. Downstream flow of combustible gases within tubing can be diluted with air to below the lower flammability limit. Analysis needs to be conducted to ensure the conditions for a flammable event are understood, and system design and operational procedures will be needed to eliminate any potentially fatal risks.

11. Risk ID #19: Tile Flammability

"If tiles do not meet safety flammability requirements, then tiles cannot be stored in an open cabin."

Preliminary flammability tests conducted at WSTF in 2013 indicate flammability results that disqualify tiles from being stored on-board ISS. Results indicate that the tiles may require Nomex or other flame-retardant coverings. Tested tiles showed smoldering for an extended time length of from 15 minutes to 1 hour. Tiles exhibited melting and dripping, with tiles of higher percentage plastics having higher flammability and longer smoldering times.[10]

12. Risk ID #5: Sudden Pressure Rise

"If a sudden rise in pressure in the TCPS occurs, such as if water flashes into vapor and steam leaks from the system, then crew safety can be at risk."

Trapped water within the trash when exposed to high temperature and heat can suddenly boil. If the steam cannot be released quickly enough through the vent ports, then high pressures in the compaction chamber will occur. Testing with the HMC Gen 1 and Gen 2 have indicated this possibility, with "push-back" being observed on the pneumatic compaction ram during higher temperature operation. Mechanical ram systems with position control need to take this into account. Pneumatic ram systems with constant pressure control can more easily adjust to a sudden pressure rise.

IV. Summary

An assessment of the technical risk for a space-based trash processing system has been conducted. Fifteen risks were identified and rated on a 5x5 likelihood vs. consequence, and then ranked accordingly. Higher risk areas were water condensation and phase separation in zero-g, and ensuring biological safety of processed trash tiles during storage. Moderate risk areas included the buildup of gunk in a TCPS after repeated operation without cleaning, managing of effluents during processing and understanding the composition and concentrations of the effluent compounds for compatibility with ECLSS air and water systems and with the VES, validating different TCPS operational scenarios, pressure regulation and control of state conditions and flow rate of gases released into the VES, the use of a catalytic oxidizer for providing source contaminant control as part of the TCPS, combustible gases and flammability limits when collected in enclosed volumes, tile off-gassing and tile flammability, and tile physical robustness and stability. An understanding of these risks, being mindful of the consequences, and active risk mitigation through subsystem performance verification will help lead to a successful TCPS design for an ISS flight demonstration and future beyond low earth orbit (LEO) missions.

Acknowledgments

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