The Trash Compaction Processing System (TCPS) Technology Demonstrations Science Objectives and Requirement Definitions

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Throughout the Next STEP Phase A and Phase B, the Trash Compaction Processing System (TCPS) is being developed for a technology demonstration (TD) on the International Space Station (ISS) in 2025. For Phase A, two contractors built proof-of-concept hardware. One contractor was chosen to build the TD hardware for Phase B. Both Phase A lessons learned and risk reduction activities at Ames Research Center (ARC) were used to write the TD science objectives, scope, and requirements. The work at ARC aims to retire technical risks and provide design data to TCPS developers and the ISS system integrators. This paper will summarize the lessons learned from the proof-of-concept hardware, the risk reduction activities, and how these lessons learned form the basis of the TD requirement matrix.

Nomenclature

AAA	=	avionics air assembly
AES	=	Advanced Exploration Systems
ARC	=	Ames Research Center
A_w	=	Water Activity
BPA	=	Brine Processor Assembly
CDRA	=	Carbon Dioxide Removal Assembly
CM	=	crew member
COTS	=	commercial off the shelf

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ECLSS = Environmental Control and Life Support Systems
EXPRESS = EXpedite the PRocessing of Experiments to the Space Station
Gen 1 = 1st Generation HMC
Gen 2 = 2nd Generation HMC
GRC = Glenn Research Center
HMC = Heat Melt Compactor
ISS = International Space Station
JSC = Johnson Space Center
LEO = Low Earth Orbit
LR = Logistics Reduction
LTL = low temperature-liquid cooling
MMI = Materials Modification Inc.
MSFC = Marshall Space Flight Center
MTL = moderate-temperature liquid cooling
NASA = National Aeronautics and Space Administration
NextSTEP = Next Space Technologies for Exploration Program
OGA = Oxygen Generator Assembly
psia = pounds per square inch, absolute
PMC = Plastic Melt Compactor
PWD = Portable Water Dispenser
RFP = request for proposal
R = risk number
RQ = requirement
SBIR = Small Business Innovation Research
SCCS = Source Contaminant Control System
SMAC = Spacecraft Maximum Allowable Concentrations
TCCS = Trace Contaminant Control System
TCPS = Trash Compaction and Processing System
T2G = Trash to Gas
TD = Technology Demonstration
TWRS = TCPS Water Recovery System
UPA = Urine Processor Assembly
UWMS = Universal Waste Management System
VES = Vacuum Exhaust System

I. Introduction

THE National Aeronautics and Space Administration (NASA) is using the International Space Station (ISS) as a testbed for the development of advanced Environmental Control Life Support System (ECLSS) technologies for exploration missions. "The purpose is to allow characterization of system performance, system reliability, and integration challenges in the relevant environment of ISS. ISS is unique in that it not only hosts a micro-gravity environment, which is essential for testing two or three phase systems such as ECLSS, but it also hosts a closed atmosphere with crewmembers providing waste products while experiencing micro-gravity. This creates highly relevant conditions which will properly challenge ECLSS systems in ways very similar to those expected during long-duration human exploration missions beyond low earth orbit.[1, 2]

Currently, the Air String[1, 2] consists of several components that are necessary for astronauts to live on the ISS. These include a particle filter, the Trace Contaminant Control System (TCCS)[3-8], the Carbon Dioxide Removal Assembly (CDRA)[9-24], the Oxygen Generation Assembly (OGA) [25-31], and the Sabatier System[14, 29, 32-38]. The Water String[1, 2] consists of the Universal Waste Management System (UWMS), the Urine Processor Assembly (UPA), Water Processor Assembly (WPA), Brine Processor Assembly (BPA), and the Potable Water Dispenser (PWD). The UPA was delivered to the ISS US lab module in 2008 and was transferred to its permanent location in Node 3 in 2010[39]. The Trash Compactor Processing System (TCPS) will be part of the Solid String. The aim of the TCPS is to reduce the trash volume, safen the trash for disposal , and/or transform the trash volume into a storable form.

On the ISS, solid waste generated aboard is currently stored and then transferred to a service module, where it is then incinerated upon reentry[40]. However, this operating scenario requires valuable crew habitat volume for storage, where the packed materials valuable resource that are not reused. In addition, biologically active waste such as residual food products or experimental wastes must currently be properly treated and stored to prevent microbial growth. For longer missions, where burn up of the trash is not a viable path, other options for managing solid waste are being considered, such as jettisoning trash to reduce habitat mass and necessary storage volume. This reduces unused mass, minimizes fuel consumption, and preserves habitable volume for crew activities. However, jettisoning may present significant challenges regarding planetary protection concerns. Therefore, compressed and safened trash could be necessary to aid in volume reduction, radiation shielding or storage considerations.

During longer space missions, where crew members (CM) must live in an enclosed environment for extended periods of time, having stored waste that occupies significant habitat volume can decrease CM morale. Therefore, NASA is exploring various solid waste treatment systems such as pyrolysis, plasma treatment, waste oxidation, Trash To Gas (T2G) [25-31], and the TCPS[41].

The TCPS technology demonstration (TD)[25-31], and the TCPS[41] as alternatives. The TCPS technology demonstration (TD) project is a flight project based on the Heat Melt Compactor (HMC) technologies developed at the Ames Research Center (ARC). In 2019, two companies were awarded the NextSTEP Phase A to build a proof-of-concept TCPS hardware. The Phase A project objectives were to 'safen' the trash, reduce its volume by 70%, and reuse the trash disks, possibly as radiation shielding. 'Safen' is defined as reducing the trash to a water activity (A_w) of less than 0.5-0.6[41], since at this A_w value, there is minimal microbial activity. Sierra Space was awarded the Next STEP Phase B[i].

When the trash is heated to safen and reduce its volume, the possibly contaminated liquid and gas effluents are fed into the downstream Air and Water String unit operations on the ISS. As a system rack, the TCPS is expected to integrate with both the Air and Water Strings as needed to recycle water and air and to interface with other ISS systems, such as the Vacuum Exhaust System (VES).

The HMC is modeled after the Navy's Plastic Melt Compactor (PMC). Figure 1 shows the development timeline of the trash compactor. In an effort to reduce trash signatures and plastic pollution in ocean waters[48, 49], the Navy uses the PMC to reshape and reduce the volume of plastics into round disks for disposal upon return to land. The HMC differs from the PMC in that, in addition to dry trash components, it also processes common space trash which includes "wet" materials such as food products. Additionally, because of the closed spacecraft environment, all gas and water effluents, including odor, must be considered before they are released into the cabin or through the various ISS subsystems. Therefore, the HMC must "safen" the trash, recover and process the water from the trash, manage the gas effluents, and reconfigure the trash as tiles. The metrics for evaluating different technologies for long-duration missions are volume, mass, power, resupply, crew time, safety, and reliability. Moreover, for Lunar or Mars exploration missions where resupply missions are infrequent or impossible, regenerable systems are preferred. For these missions, systems are designed for four CM with continuous operation for three years with minimal maintenance.

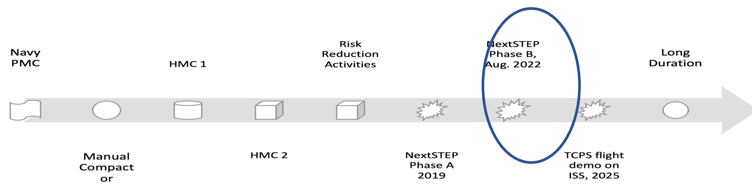


Figure 1: The TCPS/HMC development timeline

The first generation of the HMC (Gen 1) [40, 42, 43, 44] was a proof-of-concept unit designed to assess the feasibility of using trash compression technology in the spacecraft environment. The second generation HMC (Gen 2) [45, 46, 47, 48] was developed to evaluate the water and gas effluent management system. The lessons learned from Gen 1 and Gen 2 were used to define the science objectives and system requirements in the TCPS Next STEP Phase A and Phase B programs. Two contractors completed the Phase A work in 2020 [49, 50]. A technology demonstration is scheduled onboard the ISS in 2025. If the TD is successful, the TCPS will be part of the "Solid String" on the ECLSS for processing solid waste for short and long-duration space missions. Multiple papers outline the HMC Gen 1 work, HMC Gen 2 risk reduction activities, HMC-related SBIRs, the Next STEP Phase A work, and TCPS system analysis. Under the performance period for the Next STEP Phase A work, risk reduction activities were performed using the HMC Gen 2 unit at ARC. The objectives and scope of these risk reduction activities were to retire risks identified in previous HMC work. Some of these risks were identified in the Next STEP Phase A[ii] solicitation and provided data for the Next STEP Phase A contractors with their system development. Lee, et al.[51, 52] defined the TCPS technical limits and risks. These definitions were used as the drivers for risk reduction activities at ARC and as the guide for the Phase A contractors. The TCPS and HMC technologies have been in development for several decades. This paper summarizes the TCPS system descriptions, the risk reduction activities, the flight demonstration success criteria, and the requirement definitions.

The ARC risk reduction activities and how the lessons learned from these activities (coupled with those of the Next STEP Phase A work) drive the definitions of the TCPS TD objectives, scope, and requirements. Besides outlining the requirements, a discussion on the rationale of these requirements will be presented so that other subsystem designers can use them as a reference regarding the TCPS TD hardware.

A. The TCPS System Description

In parallel with the contractor's Next STEP Phase B TCPS work, ARC will continue to conduct risk reduction activities to ensure a successful TD. These activities include PM, Evolved Gas Analysis (EGA) SCCS, alternate TCPS Water Recovery System (TWRS), gunk buildup, and vent-to-VES studies. These studies will offer insights for both the TD and for long-duration operation.

[i] https://www.nasa.gov/press-release/goddard/2022/nasa-awards-demonstration-trash-compacting-system-for-iss downloaded 04/08/2023.

[ii] https://www.nasa.gov/ames/heat-melt-compactor downloaded April 8th, 2023

The TCPS has four subsystems (see Figure 2): Subsystem A: the compactor, Subsystem B: the Liquid Management and T), Subsystem C; the Gas Management System (referred to as the Source Contaminant Control System (SCCS)), and Subsystem D: the solids management system (e.g., processed TCPS tiles). Taken together, these subsystems constitute the major hardware components of the TCPS Flight Unit. TCPS Phase B requirements specify the design specifications and system requirements related to the ISS EXPRESS rack payloads, certification, safety, autonomous operation, manual operation, astronaut control, ground control, and anticipated operational scenarios. Each subsystem is described below.

1. Subsystem A: The Trash Compactor Subsystem.

Subsystem A, the compactor, is the primary component of the TCPS for reducing trash volume and stabilizing it into a compact solid and safe tile. In addition to the compactor, Subsystem A includes measures to prevent the release of hazardous particulates during processing and to contain them. This may include items such as vapor permeable bags to assist in trash processing. The aim of Subsystem A is to minimize the volume and mass of trash on the spacecraft while ensuring that it is safe for long-term storage and handling.

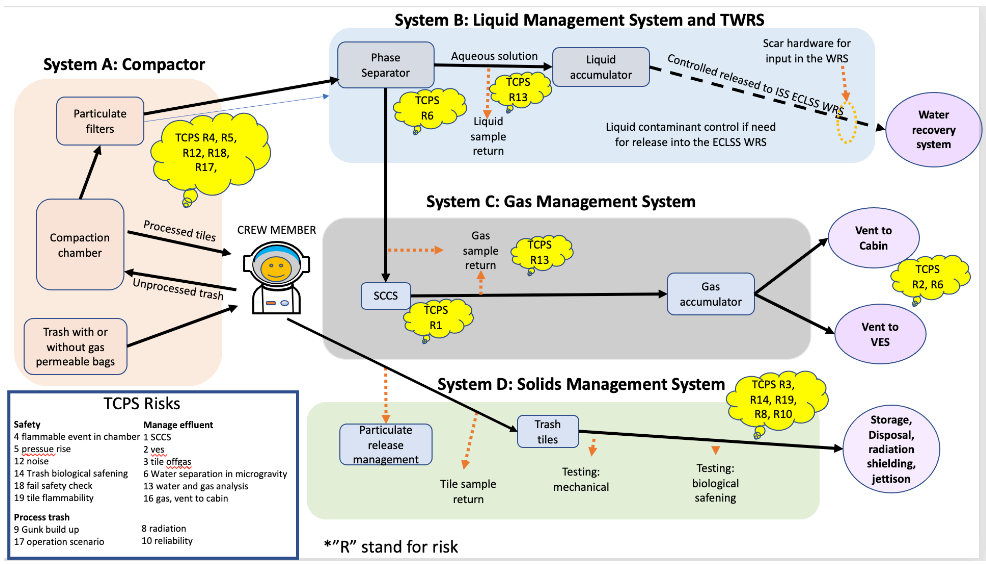


Figure 2.The TCPS and its Subsystems and associate risks. The risk matrix is listed in Appendix A. "R" is the risk number.

2. Subsystem B: The TCPS Water Recovery System and Liquid Management Subsystem.

Subsystem B consists of the TWRS and Liquid Management Subsystem. The TWRS removes water from the "wet" gas effluent stream. Various options for removing water are possible. For example, a phase separator can be used to separate liquid water, water vapor, and soluble compounds from non-condensable gases.

The Liquid Management System receives the liquid from the TWRS and stores the liquid in an accumulator. The liquid container can either be replaced when full or be emptied to the ISS WRS through a transfer line. The Technology demonstration may or may not demonstrate liquid transfer from the accumulator to the ISS WRS, hence, this capability need not be built into the delivered Flight Unit, but it should be scarred into the hardware. The TCPS must be able to collect liquid samples for return to Earth. The non-condensable gas stream that exits the TWRS is sent to Subsystem C.

3. Subsystem C: The Gas Management Subsystem

Subsystem C is responsible for managing the non-condensable gases received from Subsystem B and venting them to either the cabin or the VES depending upon the requirements for a given batch of trash. This subsystem includes gas processing methods that ensure the gases are compatible with the venting systems. Gas treatment may be necessary for either the cabin venting or VES venting, and it must satisfy the requirements for both systems. The TCPS VES assessment conducted by the ISS VES team provides a preliminary evaluation of the system's compatibility with the VES.

Possible methods for gas processing include converting non-compatible gases into compatible ones for the ISS Cabin or VES, followed by their collection in a gas accumulator for scheduled release[i] to the VES. Any proposed gas management system should consider the trade-offs between crew health, consumables, complexity, risk, reliability, and system mass, volume, and power.

4. Subsystem D: The Solid Management Subsystem

Subsystem D consists of managing solids such as processed tiles, aerosols, or particulate matter that are created and possibly released during and after tile processing. Solid particulates may be released when tiles are removed from the compaction chamber post processing. Additionally, the tiles must be mechanically stable to prevent delamination during removal and storage.

II. Risk Reduction Activities

Previous studies conducted on HMC Gen 1 included the characterization of liquid effluents, microbiological risks, and the potential flammability of the processed tiles. The goal of HMC Gen 2 risk reduction activities at ARC was to minimize unexpected issues during the TD and to collect operational data that can be used to form test objectives and define system requirements. Risks are defined so that technical challenges can be addressed in the ground-based systems. In addition, for risks that cannot be addressed solely in microgravity, ground-based data is used as a baseline.

Figure 2 shows the TCPS subsystems and the location of the identified risks. The TCPS risk matrix is listed in Appendix A. In 2019, the HMC Gen 2 risk reduction activities major objectives were: (1) standardize test methodologies; (2) retire risks; and (3) to map gas and water effluents analytical methodologies currently used on ISS to those used in the TCPS system. These test objectives are listed in Table 1. These objectives are prioritized such that the test data can be used by TCPS developers and ISS integration managers to assess design strategies for TD. Test methodologies were standardized such that the tests are repeatable, and data generated are consistent and reliable. Previous HMC Gen 1 test produce tiles and water samples, but no gas effluents data were collected. The HMC Gen 2 test campaigns involve working with the Johnson Space Center analytical laboratory to analyze the HMC gas and water effluents in the same manner as the ISS returned gas and water samples are analyzed.

Table 1: ARC Risk Reduction Activities in Fiscal Year 20 (2019-2020). The risk matrix is listed in Appendix A.

Objectives	Tasks	Outcome
Trash Input (R17)	Use standardized trash input models	Three trash models were defined and used: nominal, high liquid, and high cloths
Compactor (R4,5,12, 17, 18)	Standardize trash processing (loading, unloading, temperature profiles, pressure profiles, etc.)	Trash was loaded as is and not shredded. All trash tiles were ramped to 60˚C and then 150˚C
Water effluent characterization (R6 and 7)	Water collection Component analysis	Water collection using thermoelectric and chiller. Water samples were analyzed at the JSC analytical laboratory.
Gas effluent characterization (R1, 13)	Gas collection Component analysis	Both grab samples and continuous systems were used and characterized through EPA method TO 15 and TO 17
Tile quality (R3, 8, 10, 14, 19)	Microbial analysis Water activity	Water activity was measured both on whole tiles and on shredded tiles. Microbial analysis done on microbial strips placed on the trash.

To achieve the test objectives, three trash input models were defined and used: nominal, high liquids, and high cloths (Appendix B1). The nominal model represents common components disposed of daily by the ISS crew members; the high liquids model has higher liquid contents to account for cases when the crew does not consume all of the liquid from the drink pouch; the high cloth models represents a higher percentage of clothing and wash cloths. The details of these models are provided in the Next STEP Phase B solicitation and in Appendix B. Some variation of these trash models have been used in previous HMC testing, but here, the "same brand" of trash components were used to ensure the water and gas effluent off-gas can be reproducible. Whenever possible, ISS trash items were obtained and used instead of Commercial Off The Shelf (COTS) items. The nominal model is a representative mixture of common trash (Appendix B2) components that are typically produced by the current ISS logistics stream; and the high liquids and high cloths models are extreme cases to test the operating limits. Previously, trash were shredded and then processed in the HMC. Since the crew will most likely not shred the trash as this creates additional technical and safety risks such as dustings and requiring additional hardware, the trash components are loaded into the HMC Gen 2 as is.

Both the water and gas collection and analysis procedures were designed to retire risks. The analytical methodologies selected for the testing were mapped to those currently in use for ISS systems. Water collections included the use of a thermoelectric system, dry ice, and a chiller to recover the maximum amount of water from the effluent streams and to provide a dry effluent stream for gas analysis. These water collection methods were not designed as a system that will be used in the TD, but were configured only for the purpose of recovering the maximum

[i] Note: The VES is a carefully regulated system and access must be coordinated with ISS ground control.

volume of water to determine expected recovery rates for the various trash models and to inform the size of future TD systems. Since the HMC Gen 2 design resulted in a continuous leak from room air, thus the amount of water recovery considered the humidity input through the leak. Water samples were collected and analyzed for ions, pH, conductivity, total dissolved solids, and total solids at ARC. Additionally, water samples were sent to the JSC analytical laboratory for analysis. The JSC laboratory used the same analytical methods to test the HMC Gen 2 water samples that are used to test the water samples from the Water Recovery System on ISS.

The collection and analysis of gas effluent present significant challenges. One of the major challenges is that the TCPS and HMC operate under vacuum while most gas collection techniques are performed at atmospheric pressures. Moreover, the components present in the gas effluent can vary from one trash batch to another, and the concentrations of the components can vary significantly, making it difficult to analyze them accurately.

To address these challenges, the JSC laboratory used EPA method TO15 and TO17 to analyze the gas effluents from the TCCS system and HMC Gen 2 gas samples. Grab samples were also sent to an external laboratory for analysis, and continuous FTIR sampling methods were used inline during testing. The analytical data from these methods were compared and analyzed to ensure accuracy and consistency of results. The FTIR method was particularly useful as it analyzed for components not included in the TO15 and TO17 methods. It was found that the peak concentration of the gas effluent contaminants may occur at a time when the grab samples were not collected, thus highlighting the importance of continuous in-line sampling.

Figure 3. (A) a top view of the trash components before processing; (b) the compressed tile after processing[i]

Tile quality evaluation methods were also defined to assess the system performance throughout the test runs, including post-processing of the tiles. By evaluating the tile quality, different conditions of operation such as trash input, temperature profiles, compression pressures, water removal efficiency, and gas effluent contaminants could be evaluated. Water activity and microbial studies were conducted in parallel to assess microbial growth in the spacecraft cabin humidity environment. The water activity studies showed that the water activity value depends on various factors such as the measured location within a tile, humidity of the environment, measurement of a whole tile versus shredded samples, time of measurement, and duration of measurements. The results of these studies are discussed in Hummerick et. al. [53].

During the risk reduction test campaign using the HMC Gen 2 hardware at ARC, both liquid and gas effluents were collected from the nominal, high-liquid, and high-cloth trash models. These samples were sent to both an ISO 9001 environmental laboratory and the JSC chemical laboratory for analysis. The JSC labs analyzed the samples in the same manner as the ISS samples, and the data were presented to the ISS Boeing VES safety team.

In summary, the risk reduction activities helped to understand the operating parameters, mechanical and microbial stability of the processed tiles, and the characterization of the gas and liquid effluents. From these activities, two additional trash models were added to the TCPS: the benign and foam models. The foam model was added to reduce the volume of foam that takes up usable space on the ISS, while the benign model was added as a contingency where the gas cannot be vented to the cabin and must be vented to the VES or if the catalytic oxidizer system is not functional.

III. Flight Technology Demonstration Success Criteria

On average, four crew members are expected to produce 4.4 kg of common trash per day. The TCPS TD is designed to assess the functionality of the compression, safening, and processing of water and gas effluents in a microgravity environment, and to assess crew interactions with the proposed system.

It is also intended to assess the complexities acssociated with the effects of microgravity on crew use of the TCPS, which center around trash loading and unloading (opening the trash compactor door, insert the trash, and remove the trash tile). This activity needs to be performed with or without the assistance of foot and hand restraints. To prevent trash components from floating away in microgravity, trash bags or other containment methods can be used. The overall scope of the TCPS includes:

1. Demonstrating the use of a TCPS on the ISS, including remote monitoring and control, astronaut acceptability, astronaut feedback, and validation of the ConOps.
2. Demonstrating the value of TCPS trash processing for ISS operations and obtaining data on long-term trash management through use on the ISS.
3. Demonstrating the microgravity operational capabilities and characteristics of components and subsystems, including the TCPS Wastewater Recovery System (TWRS), accumulators, and liquid and gaseous effluent subsystems.

4. Demonstrating compatibility, integration, and acceptance with existing ISS systems, such as the ECLSS water and air systems and the ISS VES.
5. Demonstrating long-term reliability, cleaning, maintenance, and repair of the TCPS.

Figure 5 displays the objectives and success criteria for the TCPS on-orbit test, categorized into three groups: operation in microgravity, product quality, and effluent management. Human factors can be significantly different in microgravity than on Earth. Without gravity to keep the crewmember in a stationary position, operations to open and close doors, manipulate latches and handles, insert trash, remove tiles, and service and maintain the system may be difficult. Fluid (gas and liquid) behavior, including sample collection for analysis and volume storage, needs to be evaluated and verified. Any gas effluents must meet 50% of the Spacecraft Maximum Allowable Concentrations (SMAC) requirement if venting to the cabin and must meet space vacuum venting if venting to the VES. Product quality describes the heat transfer characteristics in microgravity in terms of tile density.

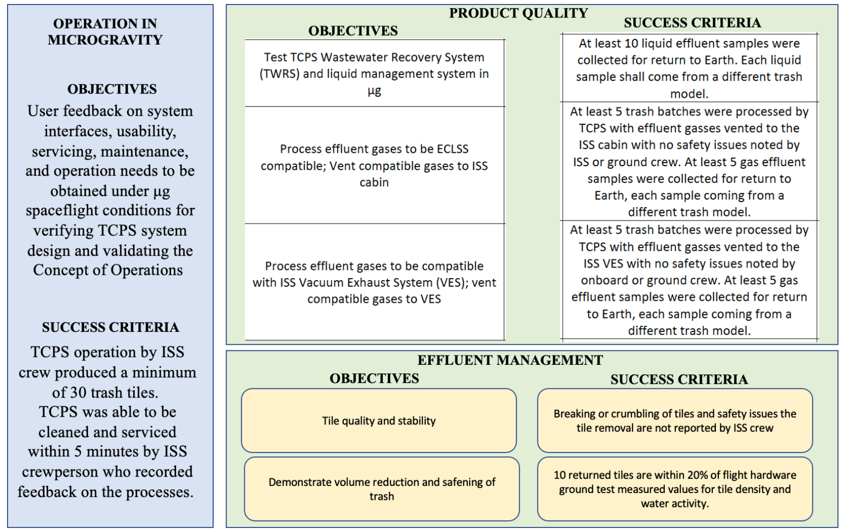


Figure 4. The TCPS on orbit test objectives and success criteria

IV. TCPS Requirement Definitions

The requirements for the flight demonstration hardware were established to meet the test objectives of the TD. The list of documents associated with these requirements are listed in Figure 6. These requirements were based on the Next STEP Phase A lessons learned, the risk reduction data collected at ARC, and collaboration with various ISS integration system managers (e.g., ISS topology, safety, and ISS ECLSS). While the hardware will primarily fit in the EXPRESS rack, the requirements also include designs for an additional system rack. For instance, the TD will collect and sample water for disposal, but the hardware will enable the liquid to be fed to the WRS if necessary. The requirements are verified by four methods according to the SSP 57000: inspection, demonstration, testing, or analysis. Reference documents are listed in the Appendix.

Document Number	Document Name
JSC-20584	Spacecraft Maximum Allowable Concentrations for Airborne Contaminants
JSC-67084	Arcturus Telemetry Project
NASA-STD-3001, Volume 1, Rev A	NASA Space Flight Human-System Standard, Volume 1, Revision A: Crew Health
NASA-STD-3001, Volume 2	NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health
NASA-STD-6001B	Flammability, Offgassing, and Compatibility Requirements and Test Procedures
NASA-STD-6016B	Standard Materials and Processes Requirements for Spacecraft
NASA-STD-8729.1.A	NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems
NPR 7120.5E	NASA Space Flight Program and Project Management Requirements (Updated w/ Change 18)
NPR 7123.1C	NASA Systems Engineering Processes and Requirements (w/Change 1)
SSP 41000	System Specification for the International Space Station
SSP 50260	Medical Operations Requirements Document (MORD)
SSP 51721	ISS Safety Requirements Document
SSP 57000, Revision T	Pressurized Payloads Interface Requirements Document

Figure 6. The list TCPS associated reference documents.

The requirements (RQ) are divided into three levels; Figure 8 shows the baseball card of the overall requirement definition for Level 1, 2, and 3. Level 1 is numbered from 1.0 to 7.0 and describes the categories throughout the entire operating space of the TCPS. Level 2 and Level 3 are subdivisions of Level 1. RQ 1.0 defines the wide range of trash models that need to be processed on the ISS, including common trash, nominal, high liquid, high cloth, foam, and benign. RQ 2.0 addresses the compactor's ability to produce a stable trash tile, which is easy to store or reuse as radiation shielding. RQ 3.0 and 4.0 define the safety and compatibility of the solid, liquid, and gas output in the cabin, as well as the interaction with other ISS subsystems and the crew, and/or venting through the vacuum exhaust system. Requirement 5.0 covers the safety of the hardware for on-orbit operations and any operation of hardware during future missions. The system must not pose a hazard to the crew, ISS systems, or ground personnel. RQ 6.0 and 7.0 specify the TCPS design and operation in the ISS EXPRESS rack and the different on-orbit testing modes.

The rationale for the RQ definition was based on previously collected data from risk reduction activities. For example, the quality of the product tile, such as density, A_w, mechanical stability, and safening, depends on the TCPS system characteristics, such as compaction pressure, operating temperature profiles, and the trash model used. For instance, the density of 375g/L is based on the 500g of nominal trash model operating at 150˚C for 3.5 hours and 55psi.

Based on the Level 1 requirements, the Level 2 requirements are further divided into categories, which include hardware design, interfaces with other ISS systems, and interactions with the crew. With regards to the trash input (RQ 1.1 to 1.3), the system shall be able to process 2.2 kg[i] of each trash model and conserve the oxygen in the trash chamber. Four crew members will produce an average of 4.4kg/day, and the TCPS is required to process 2 batches in each 24-hour period to keep up with trash production. When the trash is loaded into the compaction chamber, cabin air is trapped in the chamber, which contains oxygen. To prevent this oxygen from being vented overboard, the air volume must be recovered and recycled.

A. Category 1 Requirements: Trash Input

RQ 1.1-1.3 states that the TCPS must be able to accept and contain at least 2.2 kg/cycle of trash, in various defined trash models. All hardware materials should be compatible with the different trash types. The system must also be able to vent the initial gas volume from the unheated compressed trash volume safely to either the cabin or the VES, as required.

RQ 1.1 states that the TCPS must be capable of holding and processing a minimum of 2.2 kg/cycle of trash based on the NASA nominal TCPS trash models. This capacity takes into consideration the anticipated daily production of on-orbit waste and the available volume and ISS resources for hardware. The entire 2.2 kg load should fit into the TCPS chamber without interfering with the enclosure's door operation, including sealing, and should not allow trash to escape back into the cabin. In addition, RQ 1.1.1 states that he TCPS should be easy for a single crewmember to load and start without needing excessive physical effort, tools, or time according to SSP 57000. The system should bedesigned to allow any crewmember, regardless of physical size, strength, or capability, to operate the unit with minimal or no assistance from ground personnel. RQ 1.2 states that the TCPS must be able to accept and process various types of trash models including Nominal, High Liquid, High Cloth, Benign, and Foam TCPS trash models. This requirement is necessary to ensure that the TCPS can process different types of non-hazardous waste generated onboard the vehicle. NASA has developed these trash models to limit variability for verification purposes. RQ 1.3 states that the TCPS must be designed to allow for the venting of the initial gas volume from the unheated compressed trash volume to either the cabin or the VES as required. This is done to conserve oxygen, and the system must be designed to facilitate this process at initialization

B. Category 2 Requirements: Trash Processing

The Trash Processing RQ 2.1 to 2.5 specify certain requirements for the trash processing system.

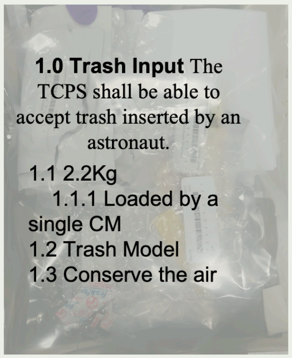
RQ 2.1 states that the system must process at least one tile in a 12 hour period, and RQ 2.2 specifies that the tile must have a density of 375g/L using the nominal trash model, which is the baseline model for most requirements. It is important to note that different trash models can produce densities that may be higher or lower than the density of the nominal model. For example, a high liquid model may produce tiles with higher densities, while a high cloth model may produce tiles with lower densities.

RQ 2.2 aims to minimize crew interactions as crew time is frequently oversubscribed and is difficult to obtain for both on-orbit operations and for training. In addition, RQ 2.2.1 states that the TCPS shall limit service to a total of 15 minutes per 15 cycles. The purpose of this requirement is to minimize minor service or cleaning of the system during continuous operation, and to ensure that it does not occupy more than the smallest schedulable increment of crew time. Ideally, the system should require little or no service during operation. Reliability and maintainability is critical to ensure that the TCPS operates efficiently with minimal downtime. Any necessary maintenance should be designed to be completed quickly and easily, without requiring excessive amounts of crew time or tools. Therefore, RQ 2.2.2 specifies a limit of 2 crew hours of maintenance every 50 cycles, which means that the TCPS should be able to operate for an extended period without requiring significant maintenance. This is important to ensure that the TCPS does notadversely impact the productivity of the ISS crew. RQ 2.2.3 states that the TCPS shall provide all unique tools

[i] The system is required to process at least 2.2kg in a 12 hour period, or up to 4.4kg per day.

5.0 Safety The TCPS shall be safe during ground testing, launch, and operation on the ISS.

5.1 The TCPS shall meet the NASA safety requirements according to SSP 51721, SSP 50260, SSP 57000, and NASA-STD-3001, during all operating conditions.
- 5.1.1 Do not allow access to the compaction chamber during operation
- 5.1.2 do no open the chamber door when not a touch temperature
- 5.2.3 shall not exceed acoustic limits



1.0 Trash Input The TCPS shall be able to accept trash inserted by an astronaut.

1.1 2.2Kg
- 1.1.1 Loaded by a single CM

1.2 Trash Model
1.3 Conserve the air

2.0 Trash Processing The TCPS shall process trash into a compacted tile

2.1 375 g/L density (nominal)
2.2 simplified crew interaction
- 2.2.1 limit service to 15 minutes/15 cycle
- 2.2.2 limit to 2 crew hours/50 cycles
- 2.2.3 provide unique maintenance tools
- 2.2.4 limit to 5 minutes of crewtime/cycle
- 2.2.5 reliability: test 20 cycle of each nominal, high liquid, foam trash model

2.3 one tile/12hours
2.4 biologically save
- 2.4.1 Aw<0.5
- 2.4.2 heat to 150˚C for 3.5 hours

2.5 tile physical integrity
- 2.5.1 volume change <5%, mass change <1%

6.0 EXPRESS Rack The TCPS shall be certified to operate in an EXPRESS Rack on the ISS.

6.1 EXPRESS rack requirements
6.2 Volume
- 6.2.1 door protrusion

6.3 Power (500W average, 750W peak)
6.4 Cooling (AAA/MTL/LTL)
- 6.4.1 when using AAA, a minimum of one tile/ 24 hours

3.0 Output The TCPS shall allow for easy and safe removal of the tile by one astronaut.

3.1 solid particle release
3.2 odor, gas, condensate, liquid
3.3 crew interaction

4.0 Effluents-All effluents from processed trash shall be managed and be compatible with ISS systems.

4.1 85% water recovered
4.2 manage the water effluent
- 4.2.1 interface: system will not start without liquid container
- 4.2.2. scar the hardware for future liquid transfer to various water recycling system
- 4.2.3 Collect water sample to return to the ground for analysis

4.3 gas effluents management (ISS cabin/VES)
- 4.3.1 Do not initiate testing until the gas processing or storage system is ready
- 4.3.2 vent gas must meet VES requirements in SSP57000
- 4.3.3 gas sample collection and return to the ground for analysis

4.4 manage solids, gunk, and particulate
4.5 manage odor
4.6 venting to cabin (SMAC)

7.0 Operational Scenarios The TCPS shall implement prescribed operational scenarios for the purpose of demonstrating technology readiness.

7.1 Vent to VES
- 7.1.1 Ability to defer venting to VES

7.2 Bent to Cabin
7.3 Autonomous processing
- 7.3.1 autonomous pause operation if lost connection to subsystems such as cooling, effluent resources, anomality, or failure

7.4 Manual operation from the front panel
7.5 Remote operation on the ground
- 7.5.1 adjustment of operating mode
- 7.5.2 Monitor and control the position of the ram in the compaction chamber
- 7.5.3 Allow control release of gaseous effluents to the VES
- 7.5.4 Allow for system interruptions and resumption

7.6 Arcturus telemetry for data transmission
- 7.6.1 Monitor, record, and transmit data
- 7.6.1 Transmit data the the DAN
- 7.6.2 Transmit data at 1Hz

Figure 8: The summary of the TCPS requirements Level 1, level 2, and level 3

required for on-orbit maintenance and reconfiguration. The design should also consider the familiarity of the crew with the tools, minimize the number of different tools required, and ensure that the tools are usable by crewmembers of different sizes and strengths while wearing protective equipment. It is recommended to use tools already available on the ISS if possible, and maintainability design should follow the guideline NASA-STD-8729. RQ 2.2.4 specifies that the average crew time for trash loading, system initiation, and tile unloading should be less than 5 minutes per cycle for all trash models. This is to minimize the impact of the TCPS on routine crew productivity and ensure that crew time is used efficiently. RQ 2.2.5 specifies that the TCPS must be tested for 20 cycles for each type of trash model (nominal, high-liquids, foam)[i] before on-orbit flight demonstration, in compliance with TCPS requirements 2.1 and 2.2.2. This ground testing is for quality assurance and proves out the system. It also provides an opportunity to demonstrate maintenance plans and procedures, such as operations procedures, maintenance schedule appropriateness, and material inspections and replacement parts appropriateness. The note accompanying this requirement specifies that the design for maintainability should follow the guideline NASA-STD-8729.

RQ 2.3 states that a tile with a density of at least 375g/L is physically stable with no delamination and can be handled by the crew without particles being released. 375g/L is a value derived from risk reduction activities completed on the HMC Gen 1 and 2. The tile density will depend on the compaction pressure and processing temperature profiles.

RQ 2.4 defines a biologically stable tile as one where the water activity is less than 0.5. Previous studies have shown that trash tiles will be biologically inactive when stored for long periods of time in humid environments and when the system processes the trash to 150°C for 3.5 hours[61]. However, the requirements did not specify the operating temperatures, but instead focus on the water activity, giving the designer the flexibility in hardware design and to ensure that the tile can be processed and stored without posing a safety risk to the crew. RQ 2.4.1 states that the TCPS tile must have a water activity of no more than 0.5 (A_w) when removed from the system to prevent microbial growth. This requirement is based on the threshold water activity needed to prevent microbial growth in food, and the minimum operating temperature specified for the safening of the trash. RQ 2.4.2 specifies that the TCPS system should uniformly heat the different types of trash models (nominal, high-liquid, and high-cloth) for a minimum of 3.5 hours at a minimum temperature of 150˚C, which is determined to be the minimum time and temperature required to ensure the tile is safe according to NASA risk reduction testing.

RQ 2.5 aims to specify the maximum allowable tile volume change such that the tile is mechanically stable for handling and delamination is not observed. For example, if the tile is removed and the crew handles it, no solid aerosol particles should be released. RQ 2.5.1 states that TCPS tile must maintain its volume and mass within 5% and 1% respectively after being physically handled by a crewmember and stored for at least 2 months to prevent hazards to the crew and ISS system. A change in mass greater than 1% may indicate a significant particle mass of the tile coming off, while a change in volume greater than 5% may indicate tile quality issues such as delamination or swelling.

C. Category 3 Requirements: Output

RQ 3.1 to 3.3 aim to specify the handling of the TCPS output such as the effluents (gas and liquid), the odor containment, the aerosol or particulates that are released, and the crew interaction of the output components.

RQ 3.1 states that the operational procedures shall manage the potential release of solid materials from trash tiles, such as particulates, according to the SSP 57000, the STD-3002, and any other applicable documents. If solid particles are released, mitigation systems or procedures shall be implemented. For example, if particles are released during tile unloading, procedures may require the crew to use the on-orbit space vacuum cleaner, or will necessitate topology to locate the rack near an intake air vent.

RQ 3.2 manages the release of odors, gases, condensate, and liquids from the TCPS and tiles into the ISS cabin. It states that these materials must be controlled to meet ISS requirements and ensure the safety and comfort of the crew and ISS systems. The management of these materials must comply with applicable documents. Verification of compliance will be achieved through analysis and testing on the ground and in orbit.

RQ 3.3 specifies that the trash tile product be removed from the TCPS by a single crewmember without requiring extreme physical effort, and to be done in a simple and low-mess manner, while minimizing crew time.

D. Category 4 Requirements: Effluents

RQ 4.1 states that the TCPS must recover at least 85% of the water from the trash during processing based on the nominal TCPS trash model. Water recovery is crucial to reduce the logistics burden and to ensure that the effluents are dry enough to be vented to the VES or cabin. The total volume of water recovered will be measured by the water

[i] Although there are five different trash models, this requirement only specifies the testing of three models.

recovery subsystem, and the percentage of water recovery will be calculated using the actual mass of water collected and the initial theoretical mass. This requirement will be verified through tests conducted both on the ground and in orbit.

RQ 4.2 states that the TCPS system must be able to manage the water coming off the trash during processing and store it in an accessible ISS-compatible container. This is necessary to collect liquid effluent for testing and/or potentially transport it to other ISS systems for processing. RQ 4.2.1 states that the TCPS process must ensure that the ISS compatible liquid storage container is connected and can accept the effluent from the next cycle before system initiation. The system must not vent untreated effluents to the cabin or VES unexpectedly and should recognize overflow potential to halt operations and prevent hazardous situations. RQ 4.2.2 states that the TCPS design shall allow for future transfer of liquid water to the ISS water recovery system by scarring the hardware, and the recovered liquid effluent should be easily transferable to the water recovery system, preferably automatically. RQ 4.2.3 specifies that the TCPS process must allow collection of water samples in dedicated containers that can be returned to the ground.

RQ 4.3 states that the TCPS must manage the gas effluent that comes off the trash during processing so that it can be vented to both the ISS cabin and VES, but not at the same time. The ISS cabin air system has specific limitations on multiple gas constituents, and the system must control the gas effluent to remain within these parameters. This requirement will be verified by analysis both on the ground and on orbit, and the effluent must meet SMAC, cabin air heat load limits, environmental interface, and active air exchange according to SSP 57000. RQ 4.3.1 states that the TCPS process must prevent system initiation if the gas contaminant control system or accumulator/storage container cannot accept the effluent from the next cycle. To prevent over-pressure situations, the system shall be able to recognize when the accumulator or gas storage is nearing its capacity limit. RQ 4.3.2 specifies that the TCPS gas effluent must meet all VES requirements stated in SSP 57000. The release of gas effluent to the VES must also comply with all ISS requirements, such as temperature, moisture content, constituents, timing of release, pressure release profile, and system availability constraints. RQ 4.3.3 states that The TCPS process must allow for the collection of gas samples that can be returned to the ground. This requirement serves the purpose of the technology demonstration and future use in determining the effluent gaseous composition for sample return to the ground for analysis.

RQ 4.4 states that the TCPS must manage solids, gunk, and particulates from trash processing without affecting its operations or interfering with ISS systems. It must be designed to contain the expected buildup and operate properly during extended durations without cleaning. Verification will be done by visual inspection and analysis of operational parameters during long-term testing.

RQ 4.5 states that the TCPS must manage and control odors to acceptable levels as per JSC-20584, SSP 57000, and NASA-STD-6001/6016. The system and its products must not be unpleasant to the crew in terms of odor.

RQ 4.6 states that if the TCPS vents gas to the ISS cabin, the trace component concentrations of the effluent gas stream must comply with the 180-day SMAC requirements as defined in SSP 41000 and JSC-20584, and must not pose any danger to the crew. The system and its processes must not release any contaminants that could endanger the health of the crew, even if they are not listed in the SMAC.

E. Category 5 Requirements: Safety

RQ 5.1 states that the TCPS must meet NASA safety requirements specified in various documents during all operating conditions, to ensure the safety of the crew and the ISS. The developer must provide documentation showing that safety requirements were met according to specified documents, and the verification methods used adhered to all pertinent safety documents. The contractor's documentation shall also include the procedures used in tests performed to verify requirements were met. The safety of the TCPS will be approved and verified by NASA ISS safety board. RQ 5.1.1 states that the TCPS must not allow access to the compaction chamber during the compaction cycle to protect the crew. The access hatch or door of the compaction chamber must be prevented from opening while a trash cycle is running. The door latch should be inoperable and unable to be opened when the cycle is running, as crew members moving inside the cabin often use surfaces to orient and propel themselves. A locked door during operations prevents unintentional unlatching of the door lock during a crew maneuver that could allow contents to escape either during or after a cycle. An automatic interlock is recommended, even if the chamber is under vacuum. RQ 5.1.2 requires the TCPS system to prevent the compaction chamber door from being opened until all exposed surfaces accessible to the operator, including both hardware and trash, meet the ISS touch temperature requirements. The system must monitor potential crew touch points to ensure that the door does not open until these requirements are met. RQ 5.1.3 states that the TCPS system must not exceed the acoustic limits specified in SSP 57000 during any phase of its operations. The system should avoid using components that are a source of noise or properly insulate them if they are required. The developer must also consider the expected lifespan of the system and take steps to ensure that the acoustic limits are not exceeded as the system ages. This may include building in margin or implementing maintenance procedures to prevent acoustic increases over time.

F. Category 6 Requirements: EXPRESS Rack

RQ 6.0 to 6.4 states that the TCPS must meet the EXPRESS Rack requirements as specified in SSP 57000. It must occupy a maximum of one, double EXPRESS locker space plus an equivalent ISIS EXPRESS drawer or 3rd locker volume and have a maximum power consumption of 500 Watts (average) and 750 Watts (peak). The TCPS must be capable of operating using avionics air assembly cooling (AAA) only, or AAA plus low-temperature liquid cooling (LTL), or AAA and the moderate-temperature liquid cooling (MTL) independently or in combination for heat rejection from the trash compactor.

RQ 6.1 states that the TCPS must be designed to meet EXPRESS Rack requirements as specified in SSP 57000. The system must also meet the requirements of the facility it is installed in, and in some cases, additional instrumentation may be required for liquid cooling loops. The contractor was advised to coordinate with the EXPRESS Rack group early in the design process.

RQ 6.2 specifies that the TCPS must occupy no more than one double EXPRESS locker space and an equivalent ISIS EXPRESS drawer or 3rd locker volume. It is strongly preferred to use the ISIS drawer over a 3rd locker due to real estate constraints on ISS. A bump out may be considered in lieu of a 3rd locker. The system must have a compact and minimal footprint, and the payload developer is expected to ensure the TCPS meets these space requirements. Furthermore, RQ 6.2.1 states that the front door assembly of the TCPS must be designed and sized in accordance with SSP 57000 to meet protrusion requirements, where the overall goal is to minimize protrusions, which can negatively impact crew operations.

RQ 6.3 states the TCPS power consumption must not exceed 500 Watts (average) and 750 Watts (peak) to avoid allocation issues with other payloads sharing the EXPRESS rack resources. Minimizing power consumption is encouraged.

RQ 6.4 states the TCPS must be able to operate using air cooling, low-temperature liquid cooling (LTL), and medium-temperature liquid cooling (MTL) both independently and in combination for heat rejection from the trash compactor. LTL is preferred for normal operations. The system must be designed to be able to use either the MTL or LTL system and must always be able to use air cooling for integration into the existing ISS smoke-detection systems. The use of liquid cooling is only required for the trash compaction chamber, phase changes, contaminant treatment system, and adjacent surfaces. LTL is the preferred cooling method because it is the most efficient, but the system must be designed to use both liquid cooling methods. RQ 6.4.1 specifies that if only AAA (Avionics Air-to-Air) is used for cooling, one tile must be processed within 24 hours. However, this requirement only applies in the specific contingency when liquid cooling (LTL and/or MTL) is not available.

G. Category 7 Requirements: Operational Scenarios

RQ7.1 to RQ 7.6 states that the TCPS must be designed to process trash on the ISS and must be able to vent gaseous effluents either to the cabin or to the VES and meet specific requirements regarding temperature, pressure, and effluent constituents. The system should also have autonomous processing capabilities to minimize astronaut interactions and provide the crew with manual control options at the front panel for mode selection, emergency stop, and restart. Ground personnel should be able to remotely monitor, operate and control system initiation, shut-down, and other operational process controls. Finally, the system must use the Arcturus Telemetry system for data transmission through the ISS to and from the ground.

RQ 7.1 states that the TCPS must have the capability to vent gaseous waste to the VES, as necessary, for any given trash batch. Venting modes must be tested and verified to meet requirements for temperature, effluent constituents, and VES venting flowrate. RQ 7.1.1 specifies that the TCPS must have the ability to defer gaseous effluent venting to the VES. However, permission to vent to VES must be explicitly granted by ISS operators prior to the operation. The TCPS system must be capable of holding gas effluent until permission is given to vent to the VES. Additionally, release of effluent gas to the VES must be controllable from the ground, as there is only a limited time window for allowable venting.

RQ 7.2 states that the TCPS shall be able to vent gaseous effluents to the cabin for any given trash batch as required. With RQ 7.1, this venting duality will improve trash batch flexibility, increase available operating cadence, and can economize gases for benign batches. The system shall be capable of venting to either the cabin or to the VES (but not both simultaneously). This requirement will be verified by analysis and test both on the ground and on-orbit according to SSP 57000, STD-6001, NASA-TM-108497. The effluent will have to meet SMAC, cabin air heat load limits, environmental interface, and active air exchange according to SSP 57000.

RQ 7.3 states that the TCPS shall be able to process trash without astronaut interaction and have autonomous processing, with the crew only required for loading and tile removal. This is to simplify and minimize crew interactions, maximize system throughput, and coexist well with other ISS systems. Activation can be immediate or delayed via ground control depending on operational constraints. RQ 7.3.1 states that the TCPS must have the ability to autonomously pause in the event of a loss of shared resources, such as cooling or effluent venting, and shut down in the case of unexpected anomalies or failures and transition into a safe mode. In such situations, the system must be able to automatically transition into a safe mode.

RQ 7.4 states that the TCPS must have a front panel that allows crew members to control the system manually for mode selection, system initiation, emergency stop, and restart. A start button is sufficient for normal trash loads, but users should have manual control functions for emergency situations and selecting appropriate trash modes. Verification of this requirement will occur through testing under all operating conditions without interfering with autonomous functions.

RQ 7.5 that ground ground personnel will be able to remotely monitor, operate, and control the system initiation, shut-down, and perform other operational process controls. This capability is intended to minimize crew interactions and allow for the TCPS to operate during scheduled times when the crew is not available or engaged, such as during crew sleep cycles or when the VES or other systems are available. RQ 7.5.1 states that the TCPS must allow for the adjustment of modes, including changing compression force and temperature profiles from the ground. This is because new or different trash or operating scenarios may require adjustments to functional or operational parameters to best deal with the trash or its effluent. This requirement is in line with the overall objective of the TCPS, to efficiently and effectively manage waste and its byproducts during spaceflight missions. In addition to allowing for adjustments in compression force and temperature profiles, as stated in section 7.5, RQ 7.5.2 states that the TCPS must also allow for ground control of the position of the ram in the compaction chamber. This feature may be required for testing purposes or maintenance. Design for maintainability should follow the guideline NASA-STD-8729, as noted in this section. The ability to control the ram position from the ground enhances the flexibility and operability of the TCPS system, allowing for easier maintenance and troubleshooting during spaceflight missions. RQ 7.5.3 states that the TCPS must allow for control of the release of gaseous effluents to the VES from the ground. The permission to vent to VES must be given manually by ISS operators. Therefore, the TCPS system must be able to hold accumulated gas effluent until permission is given to vent to the VES. The release of the effluent gas to the VES must be controllable from the ground because the window for allowable venting could occur during crew sleep cycles. This requirement emphasizes the need for precise and accurate control of the TCPS system to maintain safe and healthy conditions for the crew during spaceflight missions. RQ 7.5.4 states that the TCPS must allow for control of system interruption and resumption. The system must be capable of being safely interrupted to accommodate the optimization of ISS shared resources. For example, if another payload on the shared avionics air manifold is overheating or if power to the rack needs to be interrupted to service another payload, the TCPS system must be able to safely interrupt and resume operation without compromising the safety or health of the crew. This requirement emphasizes the importance of ensuring the safe and efficient operation of the ISS shared resources during spaceflight missions.

RQ 7.6 The TCPS must use the Arcturus Telemetry system for data transmission up and down, and must be compatible with ISS data and network systems. The payload shall provide the necessary data and interfaces to the ISS Telemetry system for power, data, and command and control connectivity. The payload shall be capable of transferring all necessary payload data in a manner that is compliant with the ISS telemetry system requirements. The payload shall be designed to be remotely monitored and controlled via ground commands. Under RQ 7.6.1, the TCPS is required to monitor, record, and transmit data of several parameters to the ground including chamber pressure, ram compression force, temperatures, ram position, door safety, TCPS VES line pressure and temperature, device settings, and power. This is important to determine best practices and understand the system's operation in microgravity. The TCPS system must transmit data to the Domain Adapter Node (DAN) per JSC-67084, Arcturus Telemetry Project Developers Guide, and ITC API Reference Manual (RQ 7.6.2). The intent of using the DAN is to control the hardware from MCC and provide real-time data to the ground. The system will be designed for fail-safe conditions, and the health and safety status will be obtained via the DAN. Users who want to access the data can submit a NAMS request.

RQ 7.7 states that the TCPS must be easily accessible for maintenance and troubleshooting, including its gas and water effluents management subsystem. The design should follow NASA-STD-8729 guidelines for maintainability to avoid the need for returning the payload to the ground for repairs during longer missions.

RQ 7.8 states that the TCPS shall allow for safe recovery and resumption of operations without requiring manual intervention by the crew. This is important to ensure that the system can continue to operate effectively even in the event of unforeseen disruptions or failures, such as loss of power. The TCPS must be designed to automatically detect and recover from such unplanned terminations of operations.

RQ 7.9 states that the TCPS must be able to operate at least two cycles per day for a minimum of 42 months with scheduled maintenance. The materials used in the TCPS must be resistant to degradation caused by thermal fluctuations and exposure to melted trash. The 42-month period includes the operation cycle for flight demonstration and extended Mars mission. The design for maintainability must follow the NASA-STD-8729 guideline. This is a hardware design requirement as opposed to reliability testing on the ground.

RQ 7.10 states that the TCPS shall monitor the leak rate of cabin air into the system during test mode. A system is necessary to detect and quantify any leaks.

V. Conclusion and Future Work

The TCPS will be designed for TD onboard the ISS in 2025. The NextSTEP Phase B Solicitation was released in November 2021 and awarded to Sierra Space in 2022. The science objectives and scope drive the requirement definitions. These definitions were based on HMC Gen 1 development, HMC Gen 2 risk reduction activities, the Next STEP Phase A data, and collaboration with the various NASA ISS systems designers. The goal of the TCPS TD hardware is to test for microgravity impacts, crew interactions, and to assess applicability of the TCPS for use in future NASA missions.

VI. Acknowledgments

The TCPS technologies have been in development for several decades. Many people were involved in the development process, making it too numerous to list here. However, we would like to specifically acknowledge John Fisher, Jeffrey Lee, Jim Broyan, Barry Finger, James Clawson, Keisha Willingham, John Hogan, and Marilyn Murakami for their contributions to advancing this technology.

Appendix A

Risk #	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	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
18	Safety	Safety Approval	If safety does not approve then flight demo may not be possible.	Program			0
8		Radiation Tiles	If the tiles cannot be used for radiation augmentation, then ??? ... This is not necessarily a risk. Radiation tile augmentation is assumed to be a benefit beyond the baseline radiation design architecture	Technical			0

Appendix B

Table B1: TCPS Trash Models

General Category	HMC Batch Constituent	Nominal	High Cloth	High Liquid	Benign
		Component Mass/batch [grams]			
Cloths	Cotton T-shirts	421.6	940.5	333.5	525.3
	Towels	201.9	413.0	146.4	230.7
Wipes	Huggies Simply Clean Wipes Fragrance Free	201.9	64.8	115.1	181.3
	Dry lab. Chem Wipes	72.7	32.4	57.5	90.6
	Disinfectant Wipes	51.1	5.0	8.9	13.9
Personal Hygiene	Nitrile Gloves	57.2	25.5	45.2	71.2
	Shampoo on Towels	17.8	7.9	14.0	22.1
	Toothpaste on Towels	9.0	4.0	7.1	11.2
	PET plastic	9.0	4.0	7.1	11.2
	Chewing Gum	17.8	7.9	14.0	22.1
	Deodorant	48.7	0.0	0.0	0.0
Paper	Computer Paper, food & packaging paper	20.7	21.9	38.9	61.2
Adhesives	Duct Tape	5.1	2.3	4.0	6.4
	Kapton Tape	3.9	1.7	3.1	4.8
	Velcro	12.2	5.4	9.6	15.2
Food Packaging and Storage	Bite size pouch	77.4	34.5	61.2	96.4
	Thermo pouch	137.0	61.0	108.3	170.7
	beverage pouch	44.5	19.8	35.2	55.5
	straw assembly	19.9	8.9	15.8	24.9
	septum adapter assembly	15.1	6.7	11.9	18.8
	rehydrateable pouch	155.7	69.3	123.2	194.0
	overwrap (white laminate food packaging)	168.6	75.1	133.4	210.1
	dessicant	15.6	6.9	12.3	19.4
	BOB	71.0	31.6	56.2	88.5
Sweat Solids	Sodium Chloride	43.8	19.5	34.6	54.6
Foods & Drinks	Beef Pattie	15.2	9.7	17.2	0.0
	Scrambled Eggs	14.2	9.0	16.0	0.0
	Beef Franks	14.5	9.3	16.4	0.0
	Macaroni & Cheese	18.1	11.5	20.5	0.0
	Tortilla	17.6	11.2	19.9	0.0
	Rice pilaf	16.3	10.3	18.4	0.0
	Sweet & Sour Chicken	28.6	18.2	32.4	0.0
	Creamed Spinach	8.8	5.6	10.0	0.0
	Orange-Pineapple Drink	26.8	17.4	102.9	0.0
	Apple Cider Drink	26.8	17.2	101.7	0.0
	Pineapple Drink	26.8	17.7	104.8	0.0
	Dried Apricots	7.1	4.5	8.0	0.0
	Peaches	16.3	10.3	18.4	0.0
	Macadamia Nuts	10.3	6.6	11.7	0.0
	Strawberries	1.03	0.66	1.2	0.0
	Vanilla Pudding	11.3	7.2	12.8	0.0
Flight Packaging Materials	Reclosable Bag	20.7	81.9	145.5	0.0
	ESD Bubble Wrap	20.7	81.9	145.5	0.0
	Total Mass (g)	**2200**	**2200**	**2200**	**2200**

Table B2: ISS Common Trash List

U.S. Clothing	U.S. Crew Preference and Miscellaneous	Office Supply Pantry	U.S./Russian Hygiene
Athletic Headband	Athletic Dyna Band	Alligator Clips	Aelita Kit
Athletic Shoes (All (Bike, Running)	Exercise Putty	Binders (all)	Comb
Athletic Supporters	Eyewear (sunglasses w/case, croakies)	Binder Clips, Clamps	Comfort Kits
Russian Clothing, etc...	Hair restraints (clips, ponytail holder)- as required	Book Clamps, Clips	Cotton Swabs
Athletic shorts	Hand Grip Assembly	Book Tethers	Container, PHK
Coveralls (Regular, heavy)	Cassette Players	Bulbs (not station lighting)	Dental Floss
Eye Band	CD Kit Assembly	Bungees, adjustable (not CheCS hardware)	Deodorants
Kamelias (all)	CD Players	Calculators	Emesis Bag Assembly
Kamelia underwear	CD Stowage Container	Cartridges (printer)	Female Hygiene Kit
Kit for females	Eggsercizer	Chair (Slingback)	Gloves Dispenser Assembly, gloves, nitrile gloves
Lightweight Clothing Kit	Fabric Kneeboard Assembly	Chart Tape	Hair Brush (all)
Montazhnik Kit	Fanny Pack (Lode, Modified, Wallet)	Clipboard (Aluminum)	Hair Clippers
Morfei Gravity System	Gripmaster (all colors)	Color Dot Labels	Hand Cream
Operator Suit	Headphone cables	Crewmember Tethers	Hygiene Disposal Bag
Opora	Leatherman tools (all)	Dictionary (all)	Lipstick
Socks (thin cotton)	Sleep Kit (Ear plugs, cords, eye covers)	Erasers	Mirrors
Sleeping Bags, inserts	Watches, watch bands	Flag Assembly	Nail Clippers
Stockings, fur	Light source headlamp assembly	Flashlights	Personal Hygiene Articles-Dental aids
Wrist band for tools	Removable pockets (all)	Headlamp Assembly (LED)	Razors (manual, electric)
Crew Preference Items	Spare bulb kit assembly	Jockstrap Headband	Soaps and Ziploc Bag
Female Undergarments	Speaker Kit assembly	Light Assembly, combination	Scissors
Gloves (Deerskin, summer, flight)	Stowage Fanny Pack	Microcassette Recorder, tapes	Shampoo
Handkerchief	Stowage Container, small assembly	Mounting Squares (removable)	Shave Cream
Jackets (Liners)	Stowage, helmet bag	Paper Clips (Lichtenberg Clamps)	Styptic Pencil
Name tags	Swiss Army Knife, Utility knife	Paper (Printer; writing; copying; engineering pads; legal; metric)	Sunblock
Shirts (long, short sleeve, sleep, T-shirt)	**Towel/Napkin Pantry**	Paper Punch	Toothbrushes
Shorts (Boxer, briefs)	Dry Napkins	Pencils	Toothpaste
Socks (Crew, tube, polartec, slipper)	Dry Towels (Terry Cloth, Waffle Weave)	Pens (all including writing, sharpies)	Tweezers
Sweaters	Huggies Wipes	Post-it notes, flags (all)	Vaseline
Trousers	I.D. Clips	Record Book	**Russian Countermeasures**
X-Static Clothing	Soap/Bodybath	Rubber Bands	Bracelet M
Sanitary Hygiene Pantry	Towels	Scissors	Expanders
Dry Wipe, Multipurpose	Washcloths	Sewing Assembly	Kentavr Device
Gloves & Dispenser Assembly	Wet Napkins	Spotlight (crewmember)	Penguin Suit
Gloves, Nitrile	Wet Towels	Tape (Kapton, Shurtape, Double-sided, Masking)	Shoes (Model 270)
Pouch Assembly	Wet Wash Dispenser Assembly	Timers	**Housekeeping/Other Pantry**
Toilet Tissue Dispenser Assembly	**Battery Pantry**	Velcro Kits	Napkins (Fungistat, Sanitary for Surfaces, SPP)
	Batteries (Chargeable, non-rechargeable)	Velcoin Kits	Wipe Assembly (Multipurpose dry wipe)
		Ziploc Bags	Vacuum Bag (wet/dry)

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