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Closing The Loop In Life Support Systems For Spaceflight And Habitation: Reutilization Of Human Excrement Through Recovery Of Potable Water And Reclamation Of Waste Materials For In-Space Additive Manufacturing

Brittany Zimmerman

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CLOSING THE LOOP IN LIFE SUPPORT SYSTEMS FOR SPACEFLIGHT AND HABITATION: REUTILIZATION OF HUMAN EXCREMENT THROUGH RECOVERY OF POTABLE WATER AND RECLAMATION OF WASTE MATERIALS FOR IN-SPACE ADDITIVE MANUFACTURING

by

Brittany Lynn Zimmerman
Bachelor of Science Mechanical Engineering, Milwaukee School Of Engineering, 2011

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Name: Brittany Zimmerman
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This document, submitted in partial fulfillment of the requirements for the degree from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

DocuSigned by:
Dr. Pablo de Leon
Dr. Pablo de Leon

DocuSigned by:
Dr. Mike Gaffey
Dr. Mike Gaffey

DocuSigned by:
Dr. Timothy Young
Dr. Timothy Young

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DocuSigned by:
Chris Nelson
Chris Nelson
Dean of the School of Graduate Studies

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Date

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Department	Space Studies
Degree	Master of Science

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Brittany Zimmerman

April 15, 2021

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EQUATIONS

NOMENCLATURE

CaCl2	Calcium dichloride
CAD	Computer Aided Design
CO	Carbon Monoxide
CO2	Carbon Dioxide
CONOPS	Concept of Operations
DAQ	Data Acquisition
DI	Deionized
DMM	Digital Multimeter
ECLSS	Environmental Control and Life Support System
EDU	Engineering Design Unit
H20	Water
ICES	International Conference of Environmental Systems
ISS	International Space Station
KCl	Potassium Chloride
LEO	Low Earth Orbit
MEL	Master Equipment List
MIS	Made In Space
NaCl	Sodium Chloride
NASA	National Aeronautics and Space Administration
PDMS	Polydimethylsiloxane
PTFE	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
RH	Relative Humidity
SMAC	Spacecraft Maximum Allowable Concentration
STOOLE	Separation Technology of On-Orbit Liquid and Excrement
TBD	To Be Determined
TBR	To Be Reviewed
TBS	To Be Supplied
TEC	Thermoelectric Chiller
UCD	Urinary Collection Device
UND	University of North Dakota
UWMS	Universal Waste Management System
WCS	Waste Collection System

ABSTRACT

The National Aeronautics and Space Administration (NASA) solicited a need for a simplified, low-temperature, and robust method for recovery of water from human solid metabolic waste. A solution is investigated, and benchtop testing is performed to prove developmental feasibility utilizing an ionomer-membrane based dehydration approach for potable water recovery. Testing is implemented with synthetic fecal matter, wet wipes, dry wipes, and nitrite gloves to inform system design. The benchtop, closed-system, dehydration testing pulls together a trade space of materials to compare efficacy of designs.

The system aims to recover upwards of 80% of the water content in the human excrement. The most conservative, worst-case scenarios are assumed in testing to ensure system functionality. The setup combines a Universal Waste Management System (UWMS) analog, gas-permeable collection bags, and a counterflow tube-and-shell membrane approach for water evaporation and removal from the human metabolic waste deposits.

Water activity is tracked to evaluate the environment with respect to microbial proliferation. If the water activity level is less than 0.6, drying and stabilization of feces can reduce odor generation and prevent microbial proliferation.

INTRODUCTION

1.1 Problem Statement

Built into the genetic code of our species is the inherent compulsion for humans to explore. With much of the Earth's landmass investigated, our ancestors looked to the sky; however, travel beyond the Karman Line imposes requirements on exploration previously ignored. Ensuring human survival in such extreme environments levies new mission considerations such as radiation protection, water reclamation, waste management, air revitalization, thermal control, and others life support necessities that were often assumed ubiquitous or taken for granted.

1.2 Research Purpose

The primary objective for this research and testing was to determine the feasibility, basic performance, and characterization of water recovery from solid waste. In addition, the feasibility of using post processed solid waste for additive manufacturing would be investigated by a third-party partner. The results of that endeavor are provided here as supplementary information in the investigation of feasibility and use of the proposed technology.

2 BACKGROUND

2.1 Human Space Exploration

Exploration of space has long fascinated the human species, but to our knowledge we have only been able to surpass the Karman line since the 20th century. We began by inventing technologies that pushed further and further into the Earth's atmosphere, until finally we had the ability to launch objects into space. Not long after this achievement, we began to launch living animals into space to test safety for human explorers. From Sputnik to our first satellites, and from Vostok 1 to the international space station (ISS) our species continues to push deeper into the cosmos around us. Exploration of the universe beyond Earth's atmosphere is now divided into two categories- crewed and uncrewed. Uncrewed missions reduce complexity in terms of developing life support systems; however, nothing satisfies our thirst for knowledge or our need for exploration like crewed space missions. As manned missions become more complex as we move further into the solar system, the necessary technologies that are needed to support life on long-duration missions and habitations become obligatory. Life support systems which revitalize breathable air, reclaim potable water, protect humans from radiation, and control thermal environments need advancements and innovation. Additional considerations are also needed that evaluate approaches for providing nutrients to the crew members and provide solutions for waste management which is unavoidable with humans in the system. The industry currently has competing philosophies and approaches to life support that need to be evaluated.

2.2 Approaches to Life Support

Supply for major life support commodities is the most critical element of any long-duration manned space mission architecture. There are currently two major approaches to providing necessary life sustaining supplies such as air, water, and food. The approaches are the physical-chemical approach and the bioregenerative approach.

2.2.1 The Physical-Chemical Approach to Life Support Systems

A physical-chemical approach can be defined as any life support system in which human is the only biological component[1]. These approaches can be either open-loop or closed-loop and rely on physical, mechanical, and chemical processes to supply water and oxygen, amongst other things. Peter Eckart explains in Spaceflight Life Support and Biospherics, “Future space habitats, though, will require that the carbon loop, the third and final part-loop in the life support system, be closed. This will only be practical if advanced life support systems can be developed in which metabolic waste products are regenerated and food is produced. Physical-chemical systems are well understood by the engineering community as they utilize comparatively simple hardware. These systems, however, are not autonomous and rely on designed consumables. Expendables such as filters and liners must be periodically replaced and moving parts have inherent lifetime issues.

2.2.2 The Bioregenerative Approach to Life Support

The bioregenerative approach to life support relies on biological systems such as microbes, bacteria, algae, and higher plants to provide the necessary commodities for survival. Bioregenerative processes based on photosynthesis can produce oxygen, scrub carbon dioxide, and aid in water purification. Some bioregenerative processes can also synthesize food which gains importance for long-duration spaceflight[1]. Biological processes are less understood by engineers, require large volumes, and are maintenance intensive.

2.2.3 Comparison of Life Support Approaches

The resupply approach (whether physical-chemical or bioregenerative) is a simple and low-mass solution for short-duration missions; however, the cumulative mass (due to continual resupply) increases linearly with lengthening mission durations. This life support approach is viable for short distance missions but the least likely candidate for application for long-duration missions, such as a mission to Mars.

Physical-chemical life support approaches are useful for short-duration spaceflight but are themselves currently incapable of producing food, a necessary component for human exploration. For this reason, it is likely an approach that will be used supplementary to other approaches.

Bioregenerative life support approaches are heavy, complex, and moderately inefficient when compared to the other approaches for life support; however, bioregeneration is the most likely to be used for long-duration missions because of the ability to provide all necessary life support commodities autonomously.

Since it is the most likely candidate for future space mission, it is important to reduce total mission mass of the systems necessary for bioregenerative life support system approaches.

2.3 The Pillars of Life Support

Life support of humans in exploration originally aim at providing air, water, and food. Habitability requirements were eventually added to the list of biological factors that needed to be controlled and expanded to physical factors that were also deemed important. Life support systems are now traditionally broken into five major areas[1].

Atmosphere management is the first major area and includes atmosphere composition control, temperature control, humidity control, pressure control, atmosphere regeneration, contamination control, and ventilation.

The second major area is that of water management which encompasses provision of potable and hygiene water and the recovery and processing of wastewater.

Food production and storage is the third major area and requires the provision of food and potentially, in some systems, the production of edible biomass as well.

The fourth major area of life support systems is crew safety. This area is responsible for fire detection and suppression, and radiation shielding.

Lastly, the waste management area is focused on the collection, storage, and processing of human waste and trash.

In this thesis we will further dive into the related areas of life support and investigate past and current methods for the management of waste.

2.3.1 Waste Management

2.3.1.1 Terrestrial Approaches to Waste Management

2.3.1.1.1 Wastewater Treatment Facilities

In the United States of America, the government is responsible for waste collection, storage, and processing.

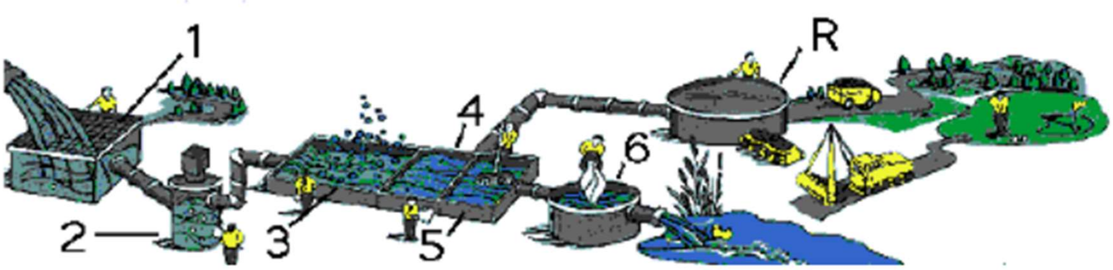


Figure 1. Wastewater Treatment Process[2]

Wastewater treatment is done in a six-step process as highlighted in Figure 1. In the first step, water arrives at the facility responsible for wastewater treatment. This influent typically contains large objects that need to be removed to avoid issues in the process. Influent can contain broken trees, large rocks, littered trash, dead animals, and more. These items are screened out of the wastewater and are typically sent to a landfill[3]. Secondly, the water is pumped into the system. Energy is a consumable required to power the pumping of the water through the system. Wastewater facilities are usually constructed below ground level such that gravity aids in the water transport process, reducing the required power for pumping. Thirdly, the water is moved into an aeration tank. Aeration is the process exposing wastewater to air through repeated agitations such as stirring, mixing, or bubbling. Often, oxygen is bubbled through a series of tanks to perform aeration. This facilitates release of some hydrogen sulfide and other dissolved gasses while replenishing the oxygen that is lost in the process of organic matter decay. Additionally, this agitation forces small particulates such as sand and other grit to settle while keeping organic material suspended. The grit is then removed and taken to landfills[3]. Fourthly, water is moved sedimentation tanks. Here the wastewater separates into layers. The previously suspended organic material in the wastewater settle to the bottom of the tanks and is now called sludge while the lighter materials such as grease, oils, plastics, and soaps, float to the top which are then referred to as scum. Fifthly, the scum is removed via rakes that sim the surfaces of the wastewater. The scrum and the sludge are both pumped into digester tanks for further processing. The digester tanks are responsible for enclosing and heating the solid wastes for approximately 30 days. Here bacteria break down, or digests, the solid wastes to kill off any organisms that cause disease and reduce the odor. Back in the sedimentation takes, the solids have been removed and the water is transported, often filtered through sand and/or carbon beds which aid in the removal of bacteria, odors, irons, solid particulates, and organic particles. Sixthly, the water flows into a tank where bacteria are killed by the addition of chlorine. The bacteria and chlorine often eliminate one another but additional chemicals may be utilized to help neutralize the chlorine in the process. The effluent is then discharged, often into a local stream or ocean[3].

2.3.1.1.2 Bioreactors

Bioreactors are often used at sewage treatment facilities to aid in the purification process. Bioreactors are an environment designed to be biologically active to promote the biochemical processes of specifically chosen organisms. This approach takes advantage of microorganisms which require organic matter and nutrients to grow, thus removing those soluble components within the medium[4]. Bioreactors are generally configured as either aerobic, which requires oxygen, or anaerobic systems which do not.

Aerobic systems are easy to operate, they minimize odors, and reduce coliforms, pathogens, and fats. However, they require large amounts of space and high operating costs[5]. Anaerobic reactors are energy-producing systems, reduces odors, and requires small volumes for operations. Challenges remain with bioreactors process whether aerobic or anaerobic. Bioreactors require control of many parameters for optimum results and produce sludge which requires additional processing[6].

2.3.1.1.3 Torrefaction

Advancements have been made in the use of torrefaction for waste management. Torrefaction is a thermochemical process to convert biomass into biochar, a coal-like material. Torrefaction reactors are classified by direct heating methods or indirect heating. Sewage sludge and other human excrement biomasses consist of fats, proteins, and other organic matter, which contain very low lignocellulose content[7]. Torrefaction may be capable of producing refuse derived fuel from large volumes of non-lignocellulosic biomass but development in this area is still being studied[8]. Torrefaction reactors are relatively new, and obstacles are still being worked out.

2.3.1.2 Past Approaches to Waste Management in Space

Approaches to waste management have certainly progressed as mission complexity and mission durations have increased. The first several humans in space were not provided with a means for waste relief. In fact, Alan Sheppard, the first American in space, was forced to urinate unplanned into his spacesuit[9]. After this a urinary collection device (UCD) was developed by NASA and utilized for short duration spaceflight[9,10]. Skylab was the first United States space toilet in which astronauts defecated into individual bags. Feces were measured and then placed under vacuum before disposal[11]. Urine was combined with lithium chloride and stored in pooling bags before disposal[11]. Eventually, a more robust toilet system was developed for the shuttle missions as part of the waste collection system (WCS). The WCS simply vented liquid waste to space. Human excrement, however, was placed into containers below deck and dried through exposure to space vacuum[12]. Lessons learned from these systems were utilized in the technology that is currently used on the International Space Station.

2.3.1.3 Current Approaches to Waste Management in Space

2.3.1.3.1 Universal Waste Management System

The International Space Station is equipped with the Universal Waste Management System. The UWMS requires crew to defecate and urinate separately. A crew member fastens themselves to the toilet to aid in holding the body against the commode in microgravity. A vacuum-hose-like device is utilized to pull the urine away from the body and into the water processing assembly[13]. For solid excrements, a lid is flipped open, exposing a circular toilet-seat opening. Inside of the opening is a gas-permeable, liquid-impermeable membrane. When the seat of the commode is opened, a blower is activated. This blower pulls a suction on the commode system. This suction provides the force necessary to keep the fecal collection bag in place while helping the fecal matter separate and move away from the crew member's body[14]. Wipes are used to clean after defecation, and those wipes are placed within the fecal collection bag before that bag is detached from the seat and dropped into the metal canister. A new bag is placed into the system for the next crew member. Every 2-3 days the metal canister is filled, and a crew member pulls the full canister from the bottom of the commode, places a filter on the top as a cap, and transports the canister to the trash for future jettison. A new canister is placed in the commode until that again is filled.

3 THE PROBLEM

The space industry desires the reclamation of water from solid wastes to enable greater water recovery during human space exploration and habitation. NASA released a solicitation for such water recovery specifically to reduce logistical burden on the International Space Station and future planetary habitation systems. Currently on the ISS, feces are collected and stored in relatively impermeable containers for short-term storage, ranging between one and three months, and then are disposed of in departing logistics vehicles. The current Universal Waste Management System produces a waste stream that consists of individual defecations and hygiene wipes collected in gas permeable bags. Between fifteen (15) and twenty-five (25) individual bags are contained in rigid containers that are changed out every two to three days. This system is logistically intense, represents the loss of precious water resources, and presents risks of biological contamination, making it an unsuitable solution for long-duration human travel beyond Low Earth Orbit (LEO).

Several other fecal processing systems including bioreactors and torrefaction systems are being developed in the industry. Bioreactors are very promising and may be an excellent solution, particularly for large installations with many crew members, but arguably have significant development risk remaining. Torrefaction is very promising and is included as a possible post-processing step and may even be considered as an upgrade in the future. However, placing solid waste directly in a torrefaction system without a permeable drying system, forces the release of all entrained water vapor and volatile compounds which must then be filtered.

4 PROPOSED TECHNOLOGY

The proposed system is an innovative Separation Technology of On-Orbit Liquid and Excrement (STOOLE) that utilizes an ionomer-membrane paired with thermal devices, scrubbers, and ancillary technologies to function as a water recovery system. The system is intended to be either a direct replacement for the current waste canister on station or a standalone assembly to be integrated nearby in Node 3.

The technology functions through use of ionomer-membrane tubes within a housing (colloquially termed: bundle), where the water molecules are able to transfer from one side of the tubule membrane to the other via a partial pressure differential. This acts as a filtration system, as only water is able to pass across the membrane. The mechanism of water transfer requires only a partial pressure differential of water be maintained across the membrane. This can be achieved with a low flow of dry air over the outside of the tubes. While NASA stated that the system does not need to purify the water, STOOLE removes the need for the downstream processing. Instead, the water vapor from the feces will cross the water transport membranes where their characterized permeance functionality greatly limits the concern for undesirable constituents in the product vapor. This vapor can be readily dispersed in the cabin and eventually condensed by the Environmental Control and Life Support System (ECLSS) already functioning on the ISS. In this effort, the feasibility basic performance of STOOLE for solid wastewater recovery will be investigated. Conceptual design, CONOPS, and packaging will also be addressed.

5 STATEMENT OF WORK

The plan is designed to have logical objectives for each task, known products that provide concrete proof that the task has been completed, and ensures the development can be met within the resources and timeframe of the project.

Table 1: Statement of Work (SOW)

Task	Task Name	Goal
1	Requirements Definition	Document system level requirements, external interfaces, and Concept of Operations.
2	Experiment Design	Design, analyze and assemble hardware to enable STOOLE functional feasibility experimentation.
3	Feasibility Experimentation	Conduct initial feasibility experimentation to ascertain fecal drying is achievable.
4	Waste Characterization for Upcycling	Understand the mechanical, physical, and chemical nature of the dried solid waste and ascertain its utility for upcycling opportunities.
5	STOOLE Prototype Conceptual Design	Use Feasibility Experimentation to inform baseline design concept via trade studies of varying options. Identify risks and potential failure modes.

5.1 Task 1: Requirements Definition

Objective: Document system level requirements, external interfaces, and Concept of Operation. In this task the top-level requirements will be refined, and requirements analysis will be performed. Presuming successful solid matter drying can be achieved, work will also be done to understand and brainstorm the various upcycling paths that may be available such as using the material in fused polymer objects or as filler/fiber material for 3D printing. Astronaut hygiene wipe samples, and UWMS bags as well as any additional compositional information that NASA may be able to provide to aid in the evaluation of the utility of these materials for dry matter upcycling will be requested.

5.2 Task 2: Experiment Design

Objective: Design, analyze and assemble hardware to enable STOOLE functional feasibility experimentation. This includes initial first principles analysis to bound major parameters, solid model development based upon analysis and consultation with the additive manufacturing vendors to create any necessary piece parts that are not commercially available. One (1) or more STOOLE bag designs will be created to allow for testing with simulated fecal matter. These bags will be of non-optimal, simple construction but allow the containment of a measured sample of fecal matter within a smaller bag similar to the current UWMS collection bags.

It is recognized that exact fecal matter may not be obtainable for feasibility testing and that acquiring fecal samples from the ISS is unfeasible for this effort. Ideally an arrangement for NASA to provide solid waste from the Astronaut Corp, fed on a diet of ISS meal packets and consistent with levels of physical activity on ISS to ensure fecal matter of a similar chemical and physical nature, is desired. If the logistics cannot be coordinated, simulated fecal matter will be created and utilized for testing. However, it is recognized that it may not be sufficiently analogous to the fecal matter produced by astronauts.

5.3 Task 3: Feasibility Experimentation

Objective: Conduct initial feasibility experimentation to ascertain fecal drying achievable with current brine dehydration systems. Using the modified developmental hardware from Task 2, basic experimentation will be conducted to validate the concept as related to the drying of solid wastes. Simple batch processing of waste will be conducted while measuring temperature and influent and outfluent gas humidity. The bag and solid waste will be weighed before and after experimentation to determine the quantity of water removed. If solid matter has been sufficiently dried in this experiment, it will be sent to Made In Space for characterization in Task 4, otherwise, alternative drying methods will be utilized to obtain sufficiently dry materials for their study.

5.4 Task 4: Water Characterization for Upcycling

Objective: Understand the mechanical, physical, and chemical nature of the dried solid waste and ascertain its utility for upcycling opportunities. In Task the dried fecal matter will be evaluated for potential upcycling applications for greater study in later efforts. Dry solid waste will be provided to Made In Space to characterize its utility to provide filler material, and reinforcement fibers that can be used within 3D print useful objects. The goal of this activity is to determine one or more means to upcycle the dehydrated waste rather than require its disposal or storage, without providing additional functionality. Made In Space will perform a basic assessment of the fecal. Using water data from these testing apparatuses, Made In Space will evaluate the basic mechanical, particle, and moisture properties of the fecal matter. This may include post processing at Made In Space's discretion to understand if slight modifications to the fecal matter will improve its utility. Made In Space possessed unique facilities that may allow the fecal matter to be tested for its utility as either a filament filler material, or as a filler material that is separately, or co-extruded to form an encapsulated volume within a part. This may allow the fecal matter to provide a useful, encapsulated filler material providing strength and thickness to 3D printed parts, saving valuable 3D printing feedstock for important peripheral and encapsulated elements.

5.5 Task 5: Conceptual Design

Objective: Use Feasibility Experimentation to inform baseline design concept via trade studies of varying options. Evaluate requirements against a verification and validation plan. Identify risks and potential failure modes. Informed by the results of experimentation, the feasibility of the technology will be assessed and a conceptual design utilizing a STOOLE system that either packages and functions within the UWMS solid waste system or is a stand-alone assembly will be generated. The possible utility and process applicability of the solid waste, wipes, bags, possibly augmented with packaging or other waste into a useful end product or into a suitable feed material for 3D printing will be evaluated with Made In Space. This assessment will lead to a conceptual design of a modified UWMS and associated systems along with rough estimations of power, mass, and volume requirements and a rough updated concept of operations (i.e., batch processing, continual operation, etc.). This design and analysis will form the basis for future development.

6 TASK 1 EXECUTION: REQUIREMENTS DEFINITION

6.1 REQUIREMENTS DEFINITION

The requirements generated here were intended to be those that applied directly to the STOOLE design, operation, and assembly. Requirements are primarily based off the solicitation and information specified by NASA. These establish the baseline to perform water recovery from fecal material. The physical interfaces and flight-relevant requirements are placed in the document as “should requirements”. Functionality and proof of effectiveness is the goal of this phase of development. While interface capability and flight readiness are desired, it is recognized as outside of the scope of this project.

6.1.1 Conventions and Notations

The convention used to indicate requirements, goals, and statements of facts is as follows:

Shall – used to indicate a requirement which must be implemented, and its implementation verified.

Should – used to indicate a goal which must be addressed by the design but is not formally verified.

Will – used to indicate a statement of fact and is not verified.

Values of quantities not yet specified are designated as:

To Be Reviewed (TBR) – used where approximate values of such quantities are known and provide useful guides for development.

To Be Determined (TBD) – used where no value is yet know.

To Be Supplied (TBS) – used where a value is known but has not been supplied to the document owner.

6.1.2 Functional Requirements

6.1.2.1 Functional Requirement 1 (FUNC-1): Water Recovery

The system shall recover a minimum of 80% of water by mass from human metabolic waste.

6.1.2.1.1 FUNC-1 Justification

Human solid waste (feces) contains approximately 75% water by mass which is currently not recovered on the ISS. Per the solicitation, technologies must be able to recover greater than 80% of the water content.

6.1.2.2 Functional Requirement 2 (FUNC-2): Water Activity Level

The system shall obtain a water activity level of less than 0.6.

6.1.2.2.1 FUNC-2 Justification

A low activity level reduces odor generation and prevents microbial proliferation. Water activity level is the partial vapor pressure of water in a substance divided by the standard state partial vapor pressure of water. Testing uses a dew point hygrometer in a close sample chamber testing. Water activity level is always a value between zero (0) and one (1).

6.1.2.3 Functional Requirement 3 (FUNC-3): Operating Temperature

The system should operate using temperatures no greater than 110°C.

6.1.2.3.1 FUNC-3 Justification

Low temperature (defined as temperature below 110°C) operation is desired to reduce the release of volatile organic compounds, avoid organic compound oxidation to CO and CO2 and their subsequent treatment prior to return to the cabin air.

6.1.2.4 Functional Requirement 4 (FUNC-4): Lifetime

The system should require replacement no more often than once every 18 months.

6.1.2.4.1 FUNC-4 Justification

The solicitation specified operation between 1 and 18 months.

6.1.2.5 Functional Requirement 5 (FUNC-5): Dormancy

The system should meet all functional requirements after a dormancy period of up to 18 months.

6.1.2.5.1 FUNC-5 Justification

The solicitation specifies dormancy periods between 11 and 18 months.

6.1.2.6 Functional Requirement 6 (FUNC-6): Drying Time

The system shall be capable of drying twenty-five (25) fecal deposits (of 75% water by mass) within [TBD] hours.

6.1.2.6.1 FUNC-6 Justification

Between fifteen (15) and twenty-five (25) individual bags are contained in rigid containers that are changed out every two (2) to three (3) days. For this requirement, the twenty-five (25) bag minimum is conservatively selected to ensure the intended operation of the system.

6.1.2.7 Functional Requirement 7 (FUNC-7): Material Compatibility

All wetted components in the system shall be compatible with human metabolic waste per [TBD].

6.1.2.7.1 FUNC-7 Justification

This requirement is meant to ensure material compatibility between the wetted system components and human waste. Currently a standard for human metabolic waste either does not exist or was not available. This requirement is intended to stay a TBD throughout the execution of this work and can be utilized as a placeholder for future development.

6.1.3 Environmental Requirements

6.1.3.1 Environmental Requirement 1 (ENV-1): Gravity Environment

The system shall be capable of meeting all functional requirements in microgravity, Lunar surface operation, or during Martian planetary surface operation.

6.1.3.1.1 ENV-1 Justification

The system is intended for use in microgravity and/or planetary surface operation on both the moon and Mars.

6.1.3.2 Environmental Requirement 2 (ENV-2): Environmental Temperature

They system shall meet all functional requirements when exposed to the ISS atmosphere temperatures ranging from 5°C to 45°C (41°F to 113°F).

6.1.3.2.1 ENV-2 Justification

On-orbit environments of the ISS.

6.1.4 Interface Requirements

6.1.4.1 Interface Requirement 1 (INT-1): Vented Constituents

The system's effluent gas stream trace component concentrations, while recovering water from the human metabolic waste, shall comply with the 180-day Spacecraft Maximum Allowable Concentrations (SMACs), found in SSP 41000, Revision CF, Table VIII.

6.1.4.1.1 INT-1 Justification

The intent of this requirement it to prevent diffusion of contaminants at a concentration that could endanger the health of the crew.

6.1.4.2 Interface Requirement 2 (INT-2): Reusability

The system shall ensure reusability of the Universal Waste Management System canister.

6.1.4.2.1 INT-2 Justification

It is desirable that the rigid Universal Waste Management System canisters be reusable to reduce logistical resupply mass.

6.1.4.3 Interface Requirement 3 (INT-3): Interface

The system should interface with the [TBD] UWMS features.

6.1.4.3.1 INT-3 Justification

The system is intended to operate onboard the ISS and have components that interface with the UWMS toilet. During this effort the aim is not to define this TBD but to leave it as a placeholder to ensure compatibility and interfacing in future development.

6.2 CONCEPT OF OPERATIONS

Notionally, STOOLE consists of a housing to replace the current canister of the ISS Universal Waste Management System, and gas permeable bags to replace the current liners, ensuring compatibility with existing hardware. A flow system will pull a closed system of warm air around the fecal containment bags, which will evaporate the water out of the feces and into the air. This air will be pulled through ionomer-membrane bundles in the flow line, where a counterflow of dry air will either pull the water out of the STOOLE system and into a condensing heat exchanger or to the ECLSS system where it can be processed. The STOOLE system is notionally placed as a stand-alone assembly, allowing canisters to be continually swapped between STOOLE and the UWMS while still being reusable. STOOLE may operate in a continuous or batch mode, to be determined, as it must allow astronauts to use the facilities on a flexible schedule. When the STOOLE cannister is full and all fecal matter has been dried, the system would be purged either to the UWMS deodorizer or vented to space to remove any undesirable gases. The STOOLE containment bag then can be removed much like a small garbage bag and the waste transferred to post processing. Alternatively, the entire assembly can be designed as a piston to allow the canister to be transferred in a sealed state and then a piston mechanism can extract the bag of dried feces. In either case, at this time the vast majority of free water has been removed from the fecal matter and any offensive odors have been removed or evacuated making the fecal matter safe to transport within its bag or container. The STOOLE containment bag will be one element of the innovation and may consist of several layers of a cellulose, paper weave, or felt with hydrophobic properties that will allow humid air to transit the bag but will not allow liquid to seep through. The goals for STOOLE include having all elements in direct contact with the fecal matter (wipes, fecal collection bags, and STOOLE bag) be disposable elements and completely constructed of organic, degradable, or pyrolizable, natural materials, allowing the bag of dried fecal product to be further processed by grinding, compaction, or torrefaction, without the complexities of mixing high resiliency polymers with the solid waste.

6.2.1 POSTPROCESSING

Having known, and well-characterized organic materials will allow a multitude of postprocessing paths that will be investigated with aid from personnel at Made In Space. Made In Space will evaluate the properties of the dry fecal matter and possibly debonded wipes and baggies to see if they would make usable filler/reinforcement for 3D printed structures. This would allow the dried fecal matter either alone, or with food packaging waste, to be used as supplementary materials encapsulated within useful parts for internal privacy dividers, floors, furniture, storage compartments, etc. On long-duration missions or planetary habitation, this would allow fecal matter to assist in the creation of products that can convert old food storage space into more useful spaces. This may also be accomplished by using the dry fecal matter as filler within a heat melt compactor. In either case, the Phase I characterization by Made In Space will help the understanding of whether the dry matter can be used as-is, or if it must be further processed through grinding, torrefaction, etc. If required, torrefaction may provide an excellent intermediary step that can possibly recover additional water, create a more consistent dried matter, and provide greater assurance of complete biological inactivity. In this effort the process for solid waste drying will be investigated and a concept of operations for both solid matter water extraction and potential postprocessing of the feces material will be determined to inform the STOOLE conceptual design. The STOOLE system will offer filtered water recovery from waste within the UWMS while also providing the opportunity for the residual matter to form useful products that maybe invaluable for long-duration exploration or planetary habitation missions.

7 TASK 2 EXECUTION: EXPERIMENTAL DESIGN

7.1.1 Verification and Validation Planning

7.1.1.1 Test

Verification by test implements a disciplined process that exercises a controlled article under a set of specified conditions, in a constrained environment, using documented procedures, measurements, and results. Verification by test is the actual operation of the item during ambient conditions or when subjected to special environments to evaluate performance. Verification by test includes laboratory, engineering design unit (EDU), and prototype tests. Verification by test also includes a thorough assessment of the data generated to determine if a required attribute is present or absent. The assessment of data derived from tests is to ensure that the proper data was collected, that it is quality data, and that the data is sufficient to fulfill the specified need. The assessment of data derived from tests is an integral part of the test program but should not be confused with verification by analysis. Test data will be used to determine quantitative compliance to requirements and produce quantitative results.

7.1.1.2 Analysis

Verification by analysis utilizes established technical or mathematical models, computer and hardware simulations, algorithms, charts, graphs, circuit diagrams, or other scientific principles and procedures to provide evidence that the specification requirements were met. Verification by analysis may be used when it can be determined that:

Rigorous and accurate verification by analysis is possible.

Verified, Validated and Accredited Models and/or Simulations are available.

Verification by test is not cost effective, practical, or physically possible. (In cases where testing is not practical, adding additional margins or higher safety factors may be an appropriate alternative.)

Verification by demonstration or inspection is not adequate.

7.1.1.3 Inspection

Verification by inspection implements the use of direct visual examination or measurement of a configuration-controlled product, design and fabrication data to confirm the presence or absence of a required attribute. Inspections include examination of data from manufacturing tools used for dimensional checks, surface finishes, and weighing, but are not intended to require significant additional analysis to evaluate compliance. Data inspected may include specifications, design documents, drawings, process specifications, compliance reports, software code listings, and static CAD models.

7.1.1.4 Demonstration

Verification by demonstration implements the use of observation to monitor and assess functionality, compatibility, or operation of a configuration-controlled product against predefined pass/fail criteria. Demonstrations can include simple quantitative measurements such as demonstration parameters, passage of time to perform actions, fit and/or functional checkout, or simple qualitative success criteria during an evaluation of product performance. A demonstration is usually an un-instrumented test conducted against documented procedures, using observation to determine if a required attribute is present or absent.

7.1.2 Functional Requirements

7.1.2.1 Functional Requirement 1 (FUNC-1): Water Recovery

The system shall recover a minimum of 80% of water by mass from human metabolic waste.

7.1.2.1.1 FUNC-1 Verification Plan

Test: Verification is considered successful when a laboratory test utilizing fecal simulant confirms 80% water recovery by mass.

7.1.2.2 Functional Requirement 2 (FUNC-2): Water Activity Level

The system shall obtain a water activity level of less than 0.6.

7.1.2.2.1 FUNC-2 Verification Plan

Test: Verification is considered successful when closed sample chamber testing confirms an activity level of less than 0.6.

7.1.2.3 Functional Requirement 3 (FUNC-3): Operating Temperature

The system should operate using temperatures no greater than 110°C.

7.1.2.3.1 FUNC-3 Verification Plan

Analysis: Verification is considered successful when analysis of system design confirms no operation which exceed 110C.

7.1.2.4 Functional Requirement 4 (FUNC-4): Lifetime

The system should require replacement no more often than once every 18 months.

7.1.2.4.1 FUNC-4 Verification Plan

Analysis: Verification is considered successful when analysis of vendor CofC and design components confirm system lifetime is at least 18 months.

7.1.2.5 Functional Requirement 5 (FUNC-5): Dormancy

The system should meet all functional requirements after a dormancy period of up to 18 months.

7.1.2.5.1 FUNC-5 Verification Plan

Analysis: Verification is considered successful when analysis of vendor CofC and analysis of design components confirm operation after 18-month dormancy.

7.1.2.6 Functional Requirement 6 (FUNC-6): Drying Time

The system shall be capable of drying twenty-five (25) fecal deposits (of 75% water by mass) within [TBD] hours.

7.1.2.6.1 FUNC-6 Verification Plan

Test: Verification is considered successful when fecal drying test data confirms drying time is within TBD hours.

7.1.2.7 Functional Requirement 7 (FUNC-7): Material Compatibility

All wetted components in the system shall be compatible with human metabolic waste per [TBD].

7.1.2.7.1 FUNC-7 Verification Plan

Analysis: Verification will be considered successful when analysis of the STOOLE Phase I Master Equipment List (MEL) confirms that wetted components are compatible with human metabolic waste using previous test data, historical use, and material specifications.

7.1.3 Environmental Requirements

7.1.3.1 Environmental Requirement 1 (ENV-1): Gravity Environment

The system shall be capable of meeting all functional requirements in microgravity, Lunar surface operation, or during Martian planetary surface operation.

7.1.3.1.1 ENV-1 Verification Plan

Analysis: Verification is considered successful when analysis of design confirms functionality in microgravity, Lunar surface operations, and Martian planetary surface operations.

7.1.3.2 Environmental Requirement 2 (ENV-2): Environmental Temperature

They system shall meet all functional requirements when exposed to the ISS atmosphere temperatures ranging from 5°C to 45°C (41°F to 113°F).

7.1.3.2.1 ENV-2 Verification Plan

Analysis: Verification is considered successful when analysis of vendor specifications and design tolerances confirm functionality in environmental temperature range.

7.1.4 Interface Requirements

7.1.4.1 Interface Requirement 1 (INT-1): Vented Constituents

The system's effluent gas stream trace component concentrations, while recovering water from the human metabolic waste, shall comply with the 180-day Spacecraft Maximum Allowable Concentrations found in SSP 41000, Revision CF, Table VIII.

7.1.4.1.1 INT-1 Verification Plan

Test: Verification is considered successful when effluent water quality is tested and is compliance with the 180-day SMACs.

7.1.4.2 Interface Requirement 2 (INT-2): Reusability

The system shall ensure reusability of the Universal Waste Management System canister.

7.1.4.2.1 INT-2 Verification Plan

Analysis: Verification is considered successful when analysis confirms material compatibility with the UWMS canister.

7.1.4.3 Interface Requirement 3 (INT-3): Interface

The system should interface with the [TBD] UWMS features.

7.1.4.3.1 INT-3 Verification Plan

Inspection: Inspection of NASA drawings which define the ISS interfaces and inspection of assembly drawings which confirm mate-ability.

7.2 Containment Bag Trade Space

A set of base materials were selected as potential candidates for the trade space of solid waste containment bags. The materials of interest were chosen because they are organic and degradable or pyrolizable natural materials, although this was not a requirement. The containment bags had to allow for the transfer of water vapor through the material while retaining the solids and liquids. In order to determine which material would be used for the fecal sample bags, a material downselect process will be performed. This process will consider several factors such as mass, cost, performance, and manufacturability. Since performance testing will be a significant factor in the down-selection process, testing of the materials was performed before the investigation of the other factors. The materials of chosen for the trade space are listed below in Table 2.

Table 2. Fecal Bag Material Trade Space

Material	Manufacturer	P/N	Cost	Performance
Polydimethylsiloxane (PDMS)	SSP	SSP-M823-005	\$18.50/ Sheet (12"x8")	barrers 10^{-9}(cc gas(RTP)cm)/(sec $cm^2 cmHg \Delta P$)
PTFE Membrane	Sterlitech	QL2312005	\$162.30 / 5pk (200mm x 250mm)	5.97-12.8 L/min·cm^2 @ 70 mbar
Unknown	NASA/TBD	TBD	TBD	TBD

The intent is to test and evaluate all three materials and evaluate for a downselect.

7.2.1 Polydimethylsiloxane (PDMS)

SSP supplies a PDMS membrane that is ultra-thin (0.005") in sheet form. Sheets are processed with a platinum cure and odor free. The data in Table 3 below is taken from the product data sheet.

Table 3. SSP-M823 product data information taken from manufacturer data sheet.

Data	Typical Values
Shore A	50
Tensile Elongation	1300 psi
Elongation	570%
Specific Gravity	1.12 – 1.16
Tear B	200 ppi
Appearance	Translucent
Operating Temperature Range	-70C(-95F) to 200C(400F)

The sheets are supplied in 12” wide rolls and cut to length. The cost of the material is $18.50 per 12” of length and $19.50 for the die cutting into 12” x 8” sheets. This gives a total of $869.50 for material and $1365.00 for cutting or $2234.50 total cost for 70 sheets.

7.2.2 Polyethylene Terephthalate (PTFE)

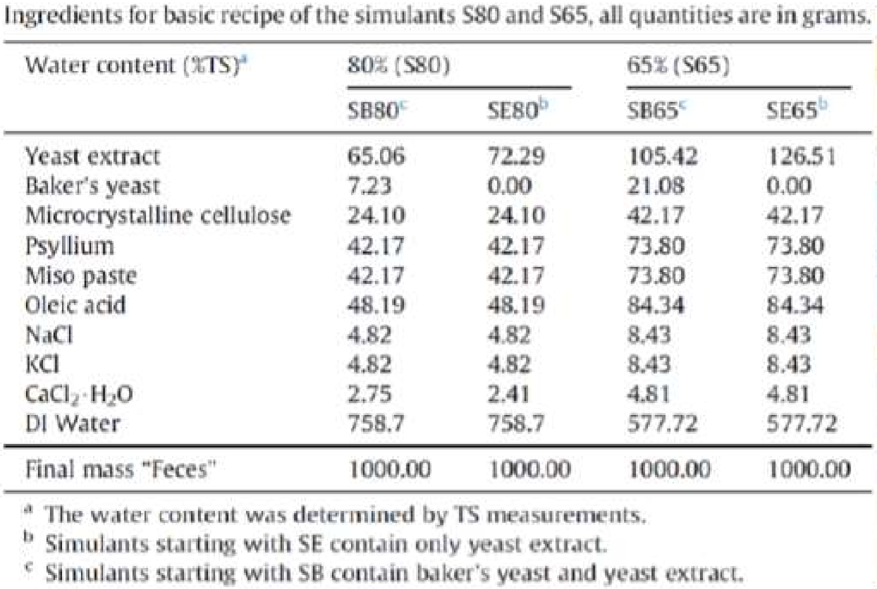
The PTFE membranes are manufactured by Sterlitech Corp. The available size is 200mm X 250mm (7.87in X 9.84in). This membrane is hydrophobic and chemically and biologically inert. The 0.2 micron pores allow 0.26-0.55 L/min·cm^2 at 70 mbar of differential pressure. The bags are priced below at $162.30 per 5-pack. Each bag requires two sheets of material which gives a total of 70 sheets needed, or 14 packs. At $162.30 each, this equates to $2272.20.

7.2.3 Current NASA Fecal Deposit Bags

The third choice of material for the trade study was the current bags that are being used for fecal deposit. These bags are known to have similar properties to the material choices above. By utilizing the bags that are already on station, implementation into the current system would be streamlined. A request for these samples from NASA was made but were not receive in time for this effort of work. Therefore, the third choice was not evaluated.

7.3 Fecal Simulant Recipe Selection

As a stretch goal, partnership with Made In Space (MIS) who specializes in space manufacturing technology may allow for future recommendations for dried material upcycling. For this dried fecal simulant samples must be provided to MIS in order for them to carry out experimentation in the use of the fecal simulant as an additive manufacturing printing medium. To begin this task, 372 kg of dried fecal matter simulant was planned for production to provide to MIS. This recipe was designed by NASA to simulate the consistency of astronaut fecal matter when in space, based on dietary intake and physical activity levels. Below, in Figure 2, are the required quantities of ingredients for synthetic fecal matter at two different water content levels that was presented in the program proposal[15,16].



Ingredients for basic recipe of the simulants S80 and S65, all quantities are in grams.

Water content (%TS)[a]	80% (S80)		65% (S65)	
	SB80[c]	SE80[b]	SB65[c]	SE65[b]
Yeast extract	65.06	72.29	105.42	126.51
Baker's yeast	7.23	0.00	21.08	0.00
Microcrystalline cellulose	24.10	24.10	42.17	42.17
Psyllium	42.17	42.17	73.80	73.80
Miso paste	42.17	42.17	73.80	73.80
Oleic acid	48.19	48.19	84.34	84.34
NaCl	4.82	4.82	8.43	8.43
KCl	4.82	4.82	8.43	8.43
$CaCl_2 \cdot H_2O$	2.75	2.41	4.81	4.81
DI Water	758.7	758.7	577.72	577.72
Final mass "Feces"	1000.00	1000.00	1000.00	1000.00

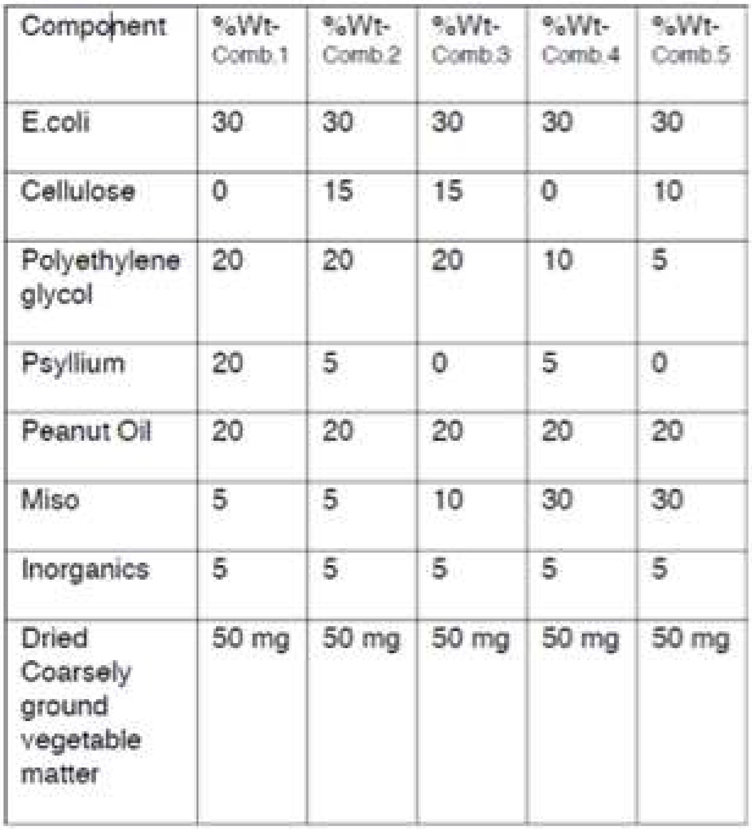
[a] The water content was determined by TS measurements.
[b] Simulants starting with SE contain only yeast extract.
[c] Simulants starting with SB contain baker's yeast and yeast extract.

Figure 2. Synthetic fecal matter recipe at 80% and 65% water content with b) sample visual.

However, NASA noted that the average water content level is around 75%. In order to determine the appropriate quantities for the average water content, the data from Figure 2 was interpolated as shown below in Table 4

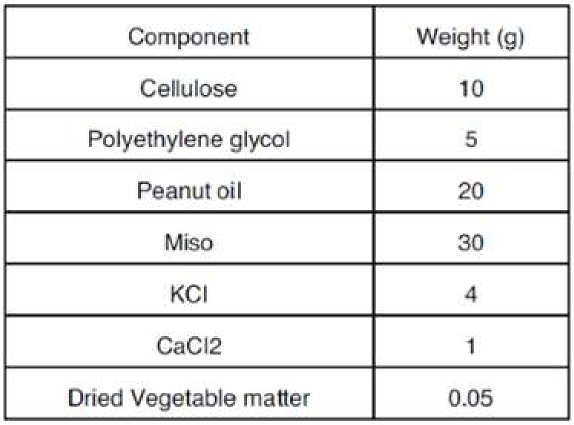
Oleic Acid does not appear in Figure 3 due to the extremely high cost and low impact on the quality/consistency of the synthetic fecal matter. For this reason, with approval from NASA, the decision was made to forgo the use of this particular ingredient. NASA also referred this program to another reference for simulant fecal material which was a paper written by Kanapathipillai Wignarajah et al. In searching for references under this name, two papers were located that had information regarding simulant fecal recipes. These papers were submitted in 2006 and 2008 at the ICES conference and can be found in the reference section of this thesis.

From Wignarajah (2006, 2008), Figure 3 and Figure 4 were referenced for possible simulant recipes.



Component	%Wt-Comb.1	%Wt-Comb.2	%Wt-Comb.3	%Wt-Comb.4	%Wt-Comb.5
E.coli	30	30	30	30	30
Cellulose	0	15	15	0	10
Polyethylene glycol	20	20	20	10	5
Psyllium	20	5	0	5	0
Peanut Oil	20	20	20	20	20
Miso	5	5	10	30	30
Inorganics	5	5	5	5	5
Dried Coarsely ground vegetable matter	50 mg	50 mg	50 mg	50 mg	50 mg

Figure 3: Fecal simulant recipe 1 collected from ICES conference paper Wignarajah et al (2006).



Component	Weight (g)
Cellulose	10
Polyethylene glycol	5
Peanut oil	20
Miso	30
KCl	4
CaCl2	1
Dried Vegetable matter	0.05

Figure 4: Fecal simulant recipes collected from ICES conference papers, Wignarajah et al (2008).

It was noted in Wignarajah (2008) that they excluded E. coli from their recipe for safety concerns which has been adopted into our current recipe. In place of this, baker's yeast and yeast extract were incorporated. The inorganics listed in Figure 3 were determined to be the salts (KCl, $CaCl_2$ and NaCl) listed in Figure 4. As with Wignarajah (2006), oleic acid was replaced with peanut oil and justified by the fact that oleic acid is the main fatty acid in peanut oil ranging from 50-80%.

Table 4. Synthetic fecal matter data interpolated to determine quantities for average water content of 75%.

	Water Content (g)		
Ingredients	80%	65%	75%
Yeast Extract	65.06	105.42	78.51
Baker's Yeast	7.23	21.08	11.85
Microcrystalline Cellulose	24.1	42.17	30.12
Psyllium	42.17	73.8	52.71
Miso Paste	42.17	73.8	52.71
NaCl	4.82	8.43	6.02
KCl	4.82	8.43	6.02
$CaCl_2$	2.75	4.81	3.44
DI Water	758.7	577.72	698.37
Peanut Oil	48.19	84.34	60.24

Human solid waste contains an average of 75% water by mass that is currently not recovered on the ISS. This is approximately 170g per crew member per day of recoverable water which translates to 0.68 kg/day for a four-person crew. In order to calculate the solids that would be left after processing through the STOOLE system, the total weight of the dried samples was calculated as shown in

Equation (1)

$$\frac{0.68\ kg\ (recoverable\ water)}{75\%\ water\ by\ mass} = \frac{x\ kg}{100\%\ total\ mass} \rightarrow \boldsymbol{x}$$

$$= \mathbf{0.9067}\ \boldsymbol{kg}\ (\boldsymbol{total\ mass\ per\ day\ for\ 4\ person\ crew})$$

Relating the 0.68 kg/day to the total mass of the water gives 0.9067 kg of total mass per day for a four-person crew, or 2.72 kg in three days. By subtracting the 0.68 kg of recoverable water from the total mass of 0.9067 kg/day, we get 0.2267 kg/day of solid waste after one hundred percent water removal.

Assuming that in the worst-case scenario, we are able to recover the minimum requirement (FUNC-1) of 80% by mass of this water, we would expect 0.544 kg for the total mass of water recovered in a 1-day period for a four-person crew, as shown below. This gives a total of 0.3627 kg of dehydrated solid waste that would be available to Made in Space for this crew size and duration. However, the recipe for fecal simulant is based on 1000g so the amount of water that will be removed from the simulant is 80% of the added DI water, or 558.7g, leaving 441.3g of dried simulant.

Equation (2)

$$\mathbf{0.68}\ \boldsymbol{kg\ x}\ \mathbf{0.8}$$

$$= \mathbf{0.544}\ \boldsymbol{kg}\ (\boldsymbol{total\ water\ mass\ after\ 1\ days\ for\ 4\ person\ crew})$$

Equation (3)

$$\mathbf{0.9067}\ \boldsymbol{kg} - \mathbf{0.544}\ \boldsymbol{kg}$$

$$= \mathbf{0.3627}\ \boldsymbol{kg}\ (\boldsymbol{Dehydrated\ solid\ waste\ after\ 1\ days\ for\ 4\ person\ crew})$$

Therefore, 80% recovery of the DI water, by mass that was put into the recipe, would equate to 558.7g. After removing this amount of water, the final weight would be 441.3g. In addition to the weight of the ingredients in the simulant recipe, the weight of nitrile gloves, dry wipes and wet wipes also need to be considered. NASA provided the usage rates for the dry wipes as listed below.

Dry Wipes (24 count)

Table 5. Dry wipe usage rates for single and three person crews per week.

		Usage Rates per Week	
Package Unit Mass (kg)	Part Number	Single Person Crew	3 Person Crew
0.057	SEZ33114924	3 Packages	10 Packages
	Total	**0.171 kg**	**0.57 kg**

Taking the summation of the single and three-person crew calculations for dry wipe usage gives a total of 0.741 kg for a four-person crew per week. Dividing this by seven days gives 0.106 kg per day. After three days, the total mass for dry wipes for a four-person crew is 0.318 kg. NASA provided guidance to consider these usage rates as a combination of both wet and dry wipes. Therefore, the total weight of wet and dry wipes will be 0.318 kg for a four-person crew, used in three days. It is assumed that the nitrile gloves are not used every deposit. Therefore, it is planned to include one pair for a period of 3 days. The approximate mass of one pair of gloves is 8 grams.

Made in Space is requesting 372g minimum of fecal simulant to include the mass of wipes and gloves. Adding the mass of the dehydrated fecal simulant, wipes and gloves for a four-person crew in a one-day period gives a total mass of 0.689 kg. In order to meet this, two batches will be prepared based on the values given in Table 1 for 75% water content.

As described in requirement FUNC-6, the available window of drying times is constrained by the removal of the canister every 2-3 days, which corresponds to approximately 15-25 individual waste bags.

The individual waste bags needed to accommodate the 2 batches would then be 30-50 bags. The approximate number of bags will be based on providing the required 1kg of material and is calculated below.

Equation (4)

$$\frac{\mathbf{0.689}\ \boldsymbol{kg}}{\mathbf{25}\ \boldsymbol{bags}} = \frac{\mathbf{.372}\ \boldsymbol{kg}}{\boldsymbol{x}} \rightarrow \boldsymbol{x} \approx \mathbf{14}\ \boldsymbol{bags}$$

Using the above equation, 14 bags need to be provided to accommodate the fecal simulant, gloves, and wipes.

8 EXECUTION: FEASIBILITY TESTING

8.1 Characterization Testing

Fecal simulant was made per the 75% water recipe shown in Table 4. Enough simulant was made for 1 crew member, for one day. The 170g of recoverable water noted above, equates to a total mass of 226.6g of solid simulant. Once mixed, the simulant quickly became gelatinous. After transferring containers, the final weight recorded was 225.4g. The simulant was weighed at several points to determine how much weight has been lost (i.e., water has evaporated) and the rate at which the evaporation took place. These results are shown in Table 6 and Figure 6.

Figure 5. Synthetic fecal matter immediately after mixing.

Table 6. Mass change of simulant left to dry in ambient conditions

Time (hrs)	Solid Mass (g)	H_20 Lost (g)	% of Total Mass Lost	% of Total H_20 Lost
0	224.6	0	0.0%	0.00%
14	203.5	21.1	9.4%	12.41%
24	189.2	35.4	15.8%	20.82%
37.5	169.7	54.9	24.4%	32.29%
48.5	151.9	72.7	32.4%	42.76%
61.5	133.5	91.1	40.6%	53.59%
88	100.1	124.5	55.4%	73.24%
96	93.5	131.1	58.4%	77.12%

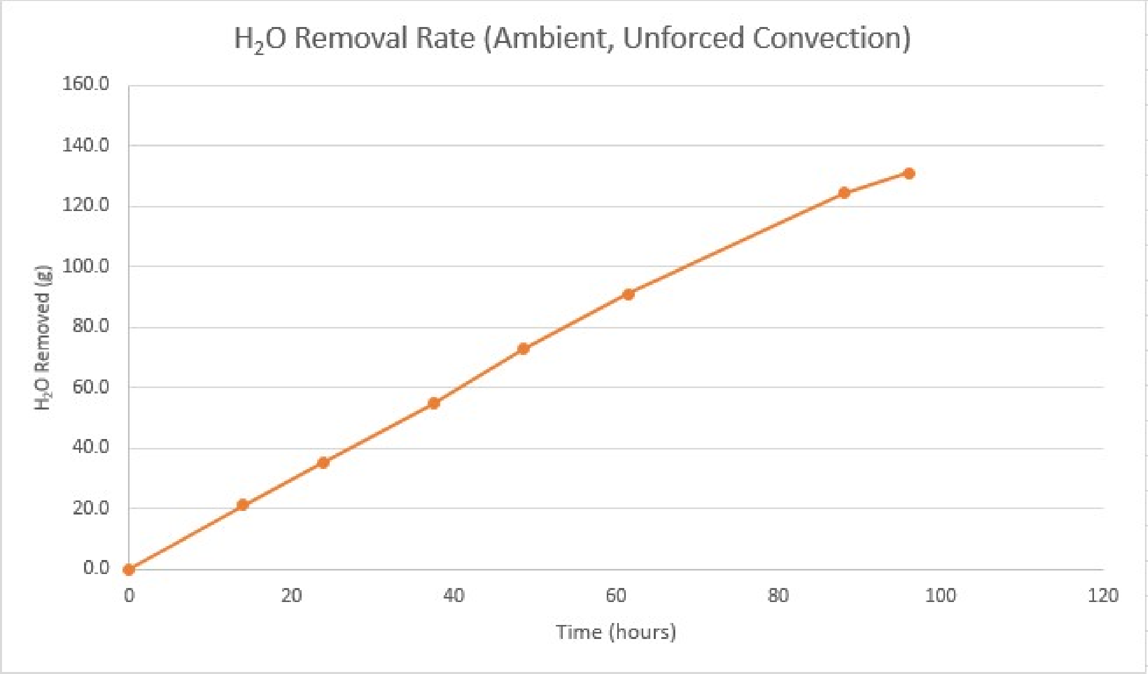


Figure 6. H_2O Removal Rate in Ambient, Unforced Convection Conditions.

8.2 Test Setup

After setting up the test bench, much time was spent ironing out flaws. Several leaks in the air path on the dirty side were identified and plugged. The airflow was too slow to overcome the check valve which was originally placed in the setup. This became a blockage point and therefore for the purposes of this testing, it was removed. The heater controller was tested with a variety of settings to determine which would hold the most constant temperature. A cutoff switch was placed just downstream of the heater on the surface of the airflow path. As a safety feature, this was then configured to turn the heater off if a max temperature was exceeded. It was discovered that the air stream temperature and path surface temperature differed by approximately 8°C.

The completed test bench is shown in Figure 7 and Figure 8. Air is passed through the PVC pipe loop, which is circulated by the gray fan in the left of Figure 7. The heater is in line with the rear PVC path behind the dark gray ionomer-membrane bundle housing. This heated air enters the bottom of the yellow igloo, which serves as the housing for the fecal simulant. The heated air removes water from the simulant and is carried downstream to a pair of ionomer-membrane bundles, which are housed in the dark gray box, shown in Figure 9. The ionomer-membrane housing is fitted with a pressure gauge to its right, and a vacuum pump to its left. The vacuum pump creates the pressure differential to encourage the water vapor molecules to cross the ionomer-membrane, where they pass through the pump to a cold plate set up with thermoelectric chillers to condense the water vapor for collection. The thermoelectric chillers attached to the cold plate with insulation can be seen in Figure 10.

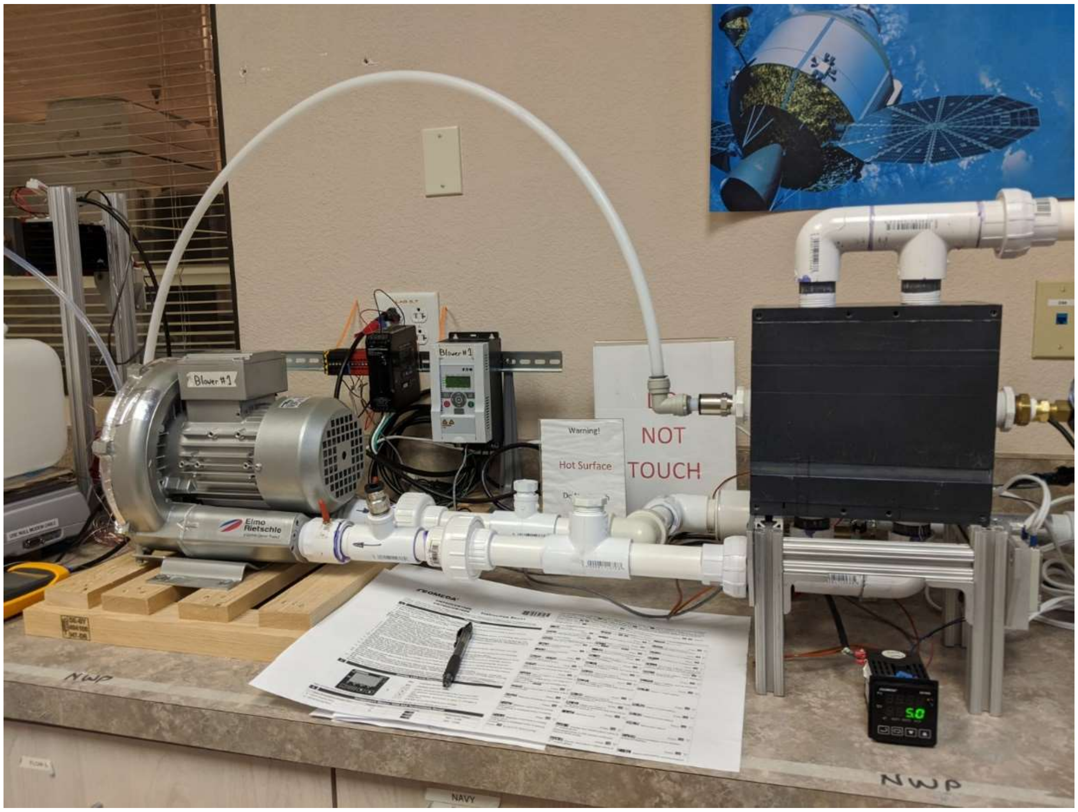


Figure 7. Initial Test Bench Set Up

Figure 8. Initial Test Bench Set Up – Right.

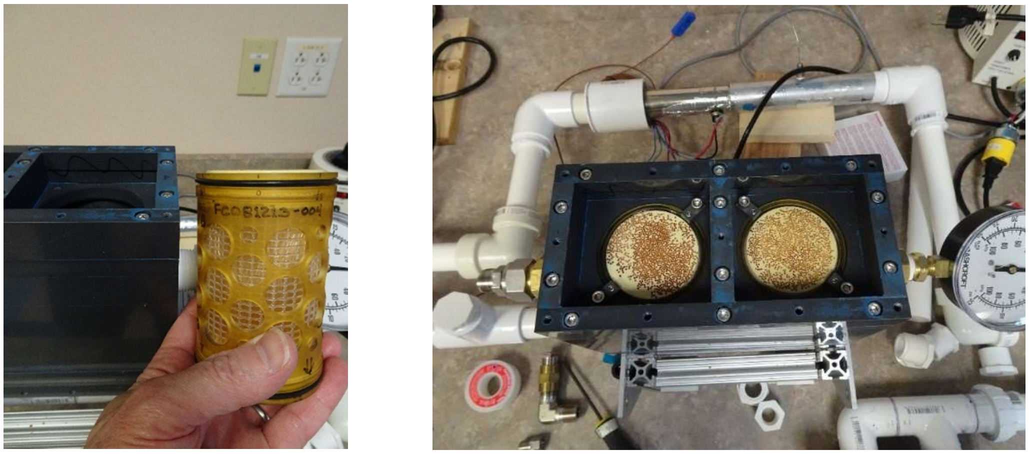


Figure 9. Ionomer-membrane Bundles (L) and Housing Installment (R).

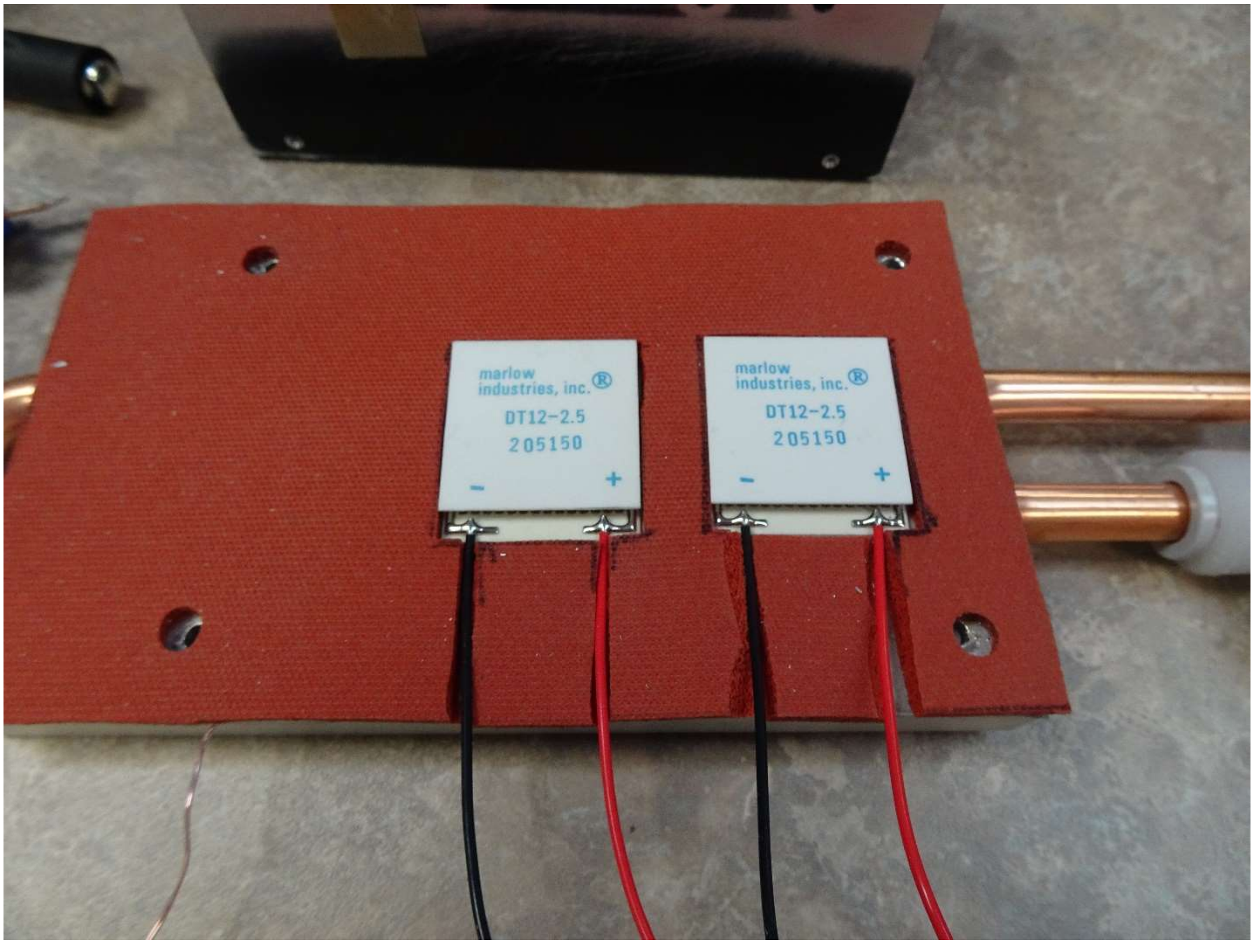


Figure 10. Thermoelectric Chillers.

Unless otherwise stated, each test was conducted with 226.6 g of simulant, mixed in accordance with the waste expected from one person per day with 75% water content. The simulant was placed in a “bag” made from 2 sheets of Sterlitech QP950 and hot glue. The PTFE membrane takes the form of a biased weave with PTFE predominant on one side, and polyester on the other. Per recommendations from Sterlitech, PTFE side of the membrane should face the simulant, i.e., form the inside of the bag. This could be readily determined given the waxy resistance from the PTFE and the fibrous and shiny nature of the polyester.

8.3 Testing

8.3.1 Room Temp Testing

The first test to use the test bench was completed without the addition of heat to compare the water lost from an ambient forced convection scenario to the ambient unforced convection conditions discussed above. Results from the testing are shown in Table 7 and Figure 11. The test was concluded after 14.5 hours because of the slow-moving process. The water removal rate of 3.98 g/hr was considerably higher than unforced convection conditions (1.4 g/hr), even without heat applied.

Table 7. Simulant Drying under Ambient Forced Convection.

Time (hrs)	**Solid Mass (g)**	**H_20 Lost (g)**	**% of Total Mass Lost**	**% of Total H_20 Lost**	**H_20 Collected (g)**	**Efficiency %**
0	224.2	0	0.0%	0.00%	0.00	0.00%
6	196.8	27.4	12.2%	16.12%	7.40	27.01%
14.5	166.9	57.3	25.6%	33.71%	10.60	18.50%

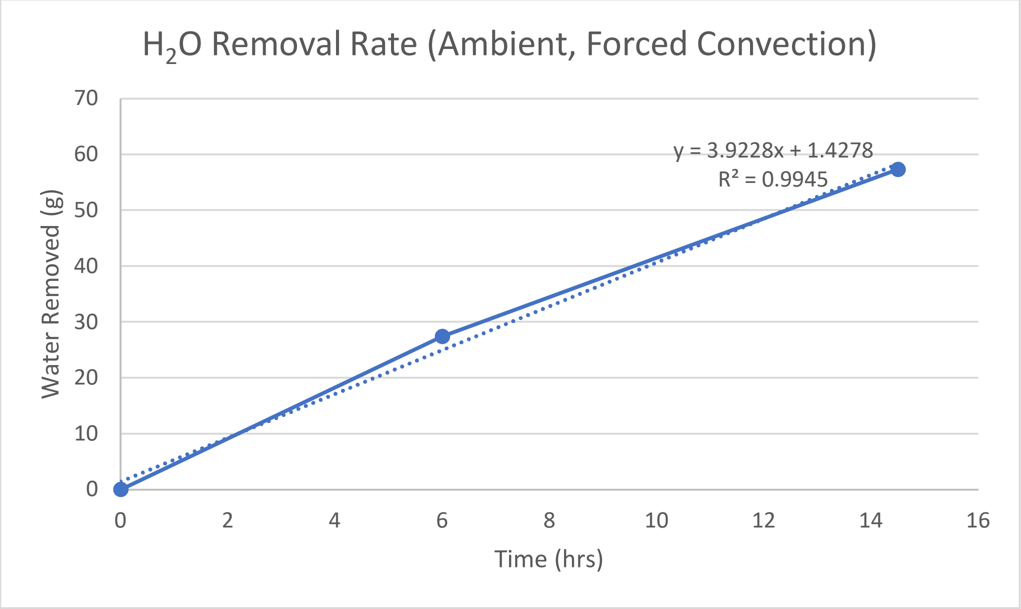


Figure 11. H_2O Removal Rate in Ambient, Forced Convection Conditions.

At the conclusion of the test, the simulant was removed from the Sterlitech bag so that it could be reused for additional testing. Although the simulant had dried somewhat, it appeared to be only the outermost layers, as visible in Figure 12. This shell had created a barrier to the moisture contained in the rest of the simulant.

Figure 12. Partially Dried Fecal Simulant.

8.3.2 Heated Testing

For the first round of testing with applied external heat, 50°C was selected to stay below the operational temperature limit of PVC (60°C). The fan speed was set to 30 Hz. A new batch of simulant was mixed and inserted into the Sterlitech bag and simulant housing. Table 8 shows the results from the testing. The vacuum pump was pulling down to about 24,000 Pa, and the thermoelectric chillers were producing temperatures of about 44°C and 6°C on the hot and cold side respectively.

Table 8. Simulant Drying at 50°C under Forced Convection.

Time (hrs)	Solid Mass (g)	Water Lost (g)	% of Total Mass Lost	% of Total H20 Lost	Water Collected (g)	Efficiency %
0	226.4	0	0.0%	0.00%	0.00	0.00%
7	180.3	46.1	20.4%	27.12%	14.40	31.24%
14	166.9	59.5	26.3%	35.00%	10.60	17.82%
21	156.4	70	30.9%	41.18%	11.60	16.57%
28	136.6	89.8	39.7%	52.82%	11.10	12.36%

Although the initial water removal rate (5.12 g/hr) and efficiency of water recovery were higher than the ambient test from above, both these quantities dropped off dramatically as the test wore on. This appeared to indicate that the ionomer-membrane bundles were getting saturated with water vapor but were unable to pull the water out into the collection chamber. There was a distinct possibility that water vapor was somehow being lost in the ionomer-membrane Bundle housing. To ascertain more clarity on the system, relative humidity sensors would need to be added into the air loop on either side of the ionomer-membrane bundle.

8.3.3 Test Bed Modifications

Several modifications were made to the test bench in a dual effort to improve performance and extract more data. Insulation was added to the air path, lining the PVC from the heater to the simulant housing. A rubber gasket was added to the igloo lid to better seal the simulant housing. The temperature cut off switch was insulated to try and bring the temperature of the air stream closer to the PVC surface temperature. And finally, Vaisala relative humidity and temperature probes were added to before and after the ionomer-membrane bundles as shown in Figure 13. Holes were drilled into the tee connections to accommodate the probes, and then sealed with putty to prevent leaks. The hardware cases were mounted to a wooden panel but were not set up with a DAQ. Relative humidity and temperature values would be taken by measuring the voltage with a DMM directly and converting per Vaisala equations.

Figure 13. Added Relative Humidity and Temperature Sensors

8.3.4 Testing with RH Sensors

Testing was restarted with a fresh batch of simulant and data was taken with the relative humidity sensors. This must be coupled with the temperature at those locations to ascertain the actual vapor pressure and the dew point temperature of the water vapor. Table 9 shows the recorded data from the first test with humidity sensors in-line.

Table 9. Relative Humidity and Temperature Measurements.

Time (hr)	Inlet RH (%)	Inlet T (°C)	Outlet RH (%)	Outlet T (°C)	Inlet Vapor P (Pa)	Outlet Vapor P (Pa)	Inlet Dew T (°C)	Outlet Dew T (°C)
0	26.68	39.9	34.81	33.7	1951	1820	17.2	16.0
1	28.35	45.6	34.88	40.1	2792	2571	23.0	21.6
2	30.23	45.1	37.11	40.7	2902	2826	23.6	23.1
3	28.38	46.3	34.3	41.1	2888	2675	23.5	22.2

Here, it is clear that the inlet and outlet water vapor pressures only have a small difference between them, indicating minimal water vapor removal. Ionomer-membrane facilitates water vapor transport through the membrane as a function of a water vapor pressure differential across the membrane. It was previously anticipated that the recirculating air on the “dirty” side of the ionomer-membrane bundle would completely saturate as water evaporated from the fecal simulant sample, providing sufficient water vapor pressure differential. However, after understanding the humidity in the recirculating air with the sensors in-line, it was clear that the vacuum pump operating at 24,000 Pa would be insufficient to remove water vapor at a sufficient rate. Instead, a vacuum pump capable of achieving pressures below the water vapor pressure on the "dirty" side of the ionomer-membrane would be necessary for positive results in testing.

The only improved vacuum pump on hand was a SOGEVAC, rotary-vane oil pump. Previous experiments had shown that this vacuum pump was tolerant of large amounts of water vapor and that it could achieve the desired pressures. While some water would likely get trapped in the vacuum pump oil during operation, the lower ultimate vacuum of the pump allowed experimentation to determine if vacuum pressure was the root cause of the poor water removal rates in previous testing. The vacuum pump was fitted with a gauge downstream of the ionomer-membrane bundle and immediately upstream of the vacuum pump inlet to confirm and record the vacuum pressure. Initial tests showed pressures of 96 Pa to 131 Pa, more than adequate for water extraction. The vacuum pump and gauge fitting are shown in Figure 14.

Figure 14. SOGEVAC SV 200 Vacuum Oil Pump

8.3.5 Testing with SOGEVAC Pump

For the next round of testing, no simulant was mixed. Paper towels were soaked in water and placed directly in the simulant housing. This would allow test results to be obtained faster and save simulant resources. All test settings were kept the same as before (heater at 50°C, fan at 30 Hz, TEC at 44°C and 6°C). Table 10 shows the test results.

Table 10. Relative Humidity and Temperature Measurements.

Time (hr)	Inlet RH (%)	Inlet T (°C)	Outlet RH (%)	Outlet T (°C)	Inlet Vapor P (Pa)	Outlet Vapor P (Pa)	Inlet Dew T (°C)	Outlet Dew T (°C)
0.5	30.91	40.0	26.82	36.7	2275	1654	19.6	14.6
2	30.48	40.0	26.48	36.8	2240	1634	19.4	14.4
4	5.89	47.2	6.61	6	627	530	0.4	-1.8
6	2.02	47.9	2.51	42.6	220	213	-13.1	-13.7

Analysis of the inlet and outlet water vapor partial pressures indicate that drying was occurring thanks to the improved vacuum pressure on the "clean" side of the ionomer-membrane bundle. The same test was repeated at higher temperatures, similar to previous tests with fecal simulant, to observe a change in drying rate as a function of air temperature. As expected, the water is removed through the ionomer-membrane at a higher rate, as seen in Table 11 compared with Table 10. Little to no water was collected in either test, indicating that most of the removed water was either getting lost to leaks, not condensing, or getting trapped in vacuum pump oil.

Table 11. Relative Humidity and Temperature Measurements.

Time (hr)	Inlet RH %	Inlet T (°C)	Outlet RH %	Outlet T (°C)	Inlet Vapor P (Pa)	Outlet Vapor P (Pa)	Inlet Dew T (°C)	Outlet Dew T (°C)
0.5	21.87	46.3	22.76	39.8	2233	1654	19.3	14.5
2	20.09	50.5	20.08	44.7	2530	1882	21.3	16.6
4	2.45	58.7	3.44	50.0	455	421	-3.9	-4.9

8.3.6 Testbed Modifications 2

After reviewing the above results and the current testbed configuration, changes were implemented to maintain uniform recirculating airflow heat and to ensure that no water vapor was lost to atmosphere before condensing. Insulation was added along the dirty air path, lining the PVC from the heater all the way to the ionomer-membrane bundle. A flow meter was inserted into the dirty loop in an effort to better quantify water recovery/removal rates. A secondary vacuum was placed after the condensation plate and water collection container to create an evacuated vessel as the exhaust reservoir in an attempt to collect all condensable water vapor exhausted by the first vacuum pump (removing residence time and mixing issues). This would require a vacuum rated container as shown in Figure 15, which was taken from another test bed. A de-mister was added to the exhaust of the vacuum pump to limit oil vapor exhaust into the water collection container.

This configuration went through several iterations, with the vacuum line being adjusted in several ways. The secondary vacuum pump was removed, and the collection line was rerouted back to the vacuum side to pull vacuum on the exhaust side initially (not during continuous operation) for better vacuum pressures. Isolation valves were added between the ionomer-membrane and vacuum pump, and another between the heat exchanger and the vacuum pump. These were opened and closed in a sequence to ensure that any excess air was exhausted to atmosphere, and the vacuum pressure was maintained at each section.

All of these tests with the vacuumed exhaust side proved once again to be unsuccessful in terms of water collection.

Figure 15. Vacuum rated water collection container

With all other likely water loss variables eliminated, the scenario of most of the water vapor being trapped in the vacuum pump oil became the last possibility to investigate. In order to prevent water vapor from entering the vacuum pump at all, a cold trap condenser was placed in-line upstream of the vacuum pump inlet. With a sufficiently low temperature cold trap, water vapor would be captured with minimal losses to the low vacuum pressure above the liquid water.

The same vacuum rated water collection container from before was repositioned in front of the vacuum pump. This was placed in an insulated cooler with dry ice to keep it cold. The thermoelectric chillers and cold plate were entirely removed from the test set-up, as the cold trap would now serve as the location for condensation collection.

8.3.7 Cold Trap Testing

The cold trap testing was conducted with a wet paper towel again, rather than simulant, to be able to quickly determine if drying and ultimately water retention was achieved. The data, calculations and results are displayed in Table 12 and

Table 13. Water vapor removal rates are estimated on the basis of an air recirculation rate of ~85 LPM, which is not directly measured, but back calculated from of the amount of condensed water collected over time, accounting for the expected amount of water removed via evaporation from the vacuum pump operating on the cold trap at its recorded temperature. Therefore, the uncertainty on the water removal rate is unquantified and likely large, but the calculated values are reported as a qualitative basis of comparison between tests. All water removal rates are calculated with the same flow rate and flow rate control remained unchanged from test to test.

Table 12. Cold Trap Testing Data.

Time (hr)	Inlet RH %	Inlet T (°C)	Outlet RH %	Outlet T (°C)	Condenser Temp (°C)	P Vapor In (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0	36.3	26.3	22.9	27.9	4	1243	1454	10.2	12.5	-7.51
1.5	38.75	45.4	38.66	38.7	5.8	3795	2663	28.1	22.1	37.30
2.5	38.38	45.7	42.46	39.8	6.5	3817	3102	28.2	24.7	22.75
3.5	37.84	46.0	41.67	40.3	6.7	3822	3127	28.2	24.8	22.09

Table 13. Cold Trap Testing Results.

Pre-Wet Paper Towel Weight (g)	109.2
Post Test Paper Towel Weight (g)	31.4
Water Removed (g)	77.8
Water Collected (g)	40.6
% Retention	52.19%

This was the first test conducted that yielded significant water recovery. The paper towel was noticeably warm and had dried substantially. With 52% water recovery, focus could now be turned to improving the yield. Although the cold trap surface temperature was relatively stable over the test duration, and well below the dew point of the water vapor exiting the ionomer-membrane, much of the water that was not recovered was likely lost through the exhaust of the vacuum pump. With the vacuum pulling to pressures of 1 torr (133 Pa), the water vapor either did not sufficiently cool to condense or was evaporated and pulled through the vacuum exhaust after condensing. Further reducing the temperature of the cold trap became the focus of the next effort of improving water collection. In addition, measurement intervals would be reduced to improve the resolution of the water vapor removal trend. The data for this lower temperature cold trap are shown in Table 14 and Table 15.

Table 14. Cold Trap Testing Data.

Time (hr)	Inlet RH %	Inlet T (°C)	Outlet RH %	Outlet T (°C)	Bath Temp (°C)	P Vapor In (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0.25	42.12	34.9	49.28	28.5	-7.8	2358	1919	20.1	16.9	14.27
0.75	40	44.4	51.4	35.7	-3.2	3721	3007	27.7	24.1	21.90
1.25	38.2	45.9	45.9	38.4	-3.2	3838	3111	28.3	24.7	22.60
1.75	37.7	46.1	43.7	39.5	-3.4	3827	3142	28.2	24.9	21.41
2.25	37.45	46.3	42.72	40.1	-2.6	3841	3172	28.3	25.0	19.73
2.75	37.43	46.3	42.39	40.3	-1.7	3839	3181	28.3	25.1	20.64
3.25	36.86	46.5	41.67	40.5	-2.1	3819	3160	28.2	25.0	20.68
3.75	33.81	47.1	39.83	40.6	-1.6	3611	3037	27.2	24.3	17.65
4.25	39.66	36.2	41.7	31.6	0.3	2385	1940	20.3	17.0	14.84
4.75	29.6	45.8	41.35	36.5	0.9	2959	2528	23.9	21.3	12.31
5.25	19.66	49.9	27.66	40.4	1.5	2416	2087	20.5	18.2	9.12
5.75	13.06	51.6	18.02	42.6	1.9	1746	1527	15.4	13.3	5.97

This test was run to completion, and the paper towel was completely dry once removed. Peak water removal rates appeared to be achieved after about an hour, ultimately a positive sign for the final application. The outlet air temperatures are lower than the inlet, as expected. Although the relative humidity was higher at the outlet, by using the temperature to find absolute humidity values (or water vapor partial pressures and dew point temperatures), it can be quickly determined that the total water vapor is indeed less as the outlet. A plot of the water vapor partial pressure at the inlet and outlet of the ionomer-membrane bundle on the "dirty" side over time, as well as their difference, during the test is shown in Figure 16. The trend in partial pressure difference shows a rise to steady state conditions, and then a decrease in removal rate as water availability on the "dirty" side decreases.

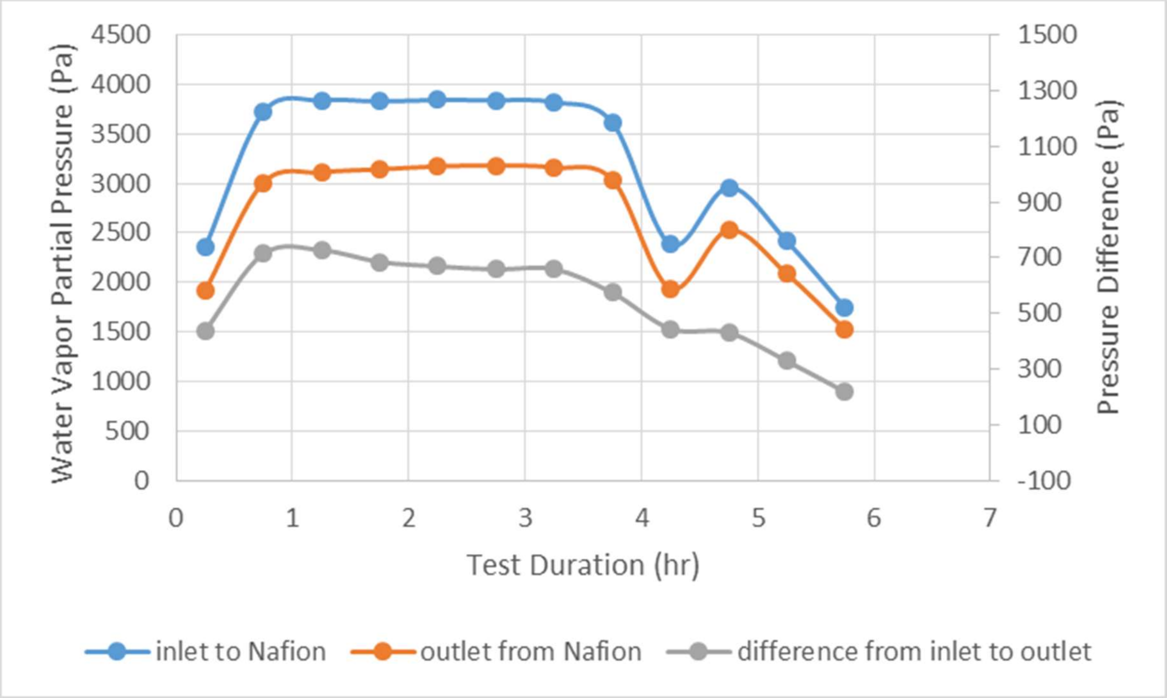


Figure 16. Water Vapor Partial Pressure at ionomer-membrane Inlet, Outlet, and their difference over time during 2nd round of cold trap testing

Table 15. Cold Trap Testing Results.

Pre-Wet Paper Towel Weight (g)	98.8
Post Test Paper Towel Weight (g)	14.6
Water Removed (g)	84.2
Water Collected (g)	61.2
% Retention	72.68%

The recorded 73% water recovery is quite close to the goal of 80%, and it is very likely that a much higher actual recovery efficiency is artificially lowered by the test set up and duration of the test than by actual recovery potential. First, the temperature in the cold trap was not constant due to the diminishing amount of dry ice available and the rejected heat from water condensation heating up the bath temperature over time, in addition to heat losses to the environment from the cold trap bath over the 6-hour test. As stated above, as the cold trap warms, water vapor becomes increasingly likely to pass through the cold trap and out the vacuum exhaust before condensing. Additionally, any vapor that condensed at the start of the test at -7.8 °C has the potential to evaporate again as the cold trap temperature rises. This likelihood increases the longer the test continues, so it’s quite possible that had the test been stopped earlier, water retention percentage could have been higher. At the end of the test, the air loop still showed levels of humidity, indicating there was more water to collect that was lost upon ending the test. And finally, any leaks along the air path will contribute to a lowered water retention rate.

With the encouraging results from above, testing could switch back to using fecal simulant in the chosen bag material.

8.3.8 PDMS Bag Testing

Although the Sterlitech material had been used for the few test completed previously, PDMS was the desired choice moving forward for testing. Once again, simulant was mixed and placed within a sheet of PDMS. The results are shown in Table 16 and Table 17.

Table 16. PDMS and Simulant Testing Data.

Time (hr)	Inlet RH %	Inlet T (°C)	Outlet RH %	Outlet T (°C)	Bath Temp (°C)	P Vapor In (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0.5	7.86	47.1	12.71	35.7	-12.6	840	744	4.4	2.7	2.36
1	5.39	50.8	8.03	40.8	-12.3	693	619	1.7	0.2	1.85
1.5	4.38	51.9	6.21	43.3	-11.8	594	546	-0.4	-1.6	1.14
2	3.94	52.3	5.43	43.8	-11	545	490	-1.6	-3.0	1.43
2.5	3.59	52.8	4.88	44.7	-10.5	509	461	-2.5	-3.8	1.22

Table 17. PDMS and Simulant Testing Results.

Pre-Simulant Weight (g)	105.4
Post Simulant Weight (g)	98.6
Water Removed (g)	6.8
Water Collected (g)	0
% Retention	0.00%

During testing, it became immediately apparent that despite similar temperature drops as found in previous testing, the relative humidity values were far lower than normal. Therefore, the test was stopped short of completion after 2.5 hours, and the simulant had lost little to no water mass and no water was collected. It was suspected this was due to a couple of reasons. First, it was possible that the highly gelatinous nature of the simulant was locking the water inside the simulant. The psyllium is the primary ingredient responsible for gelling the simulant, and given the airflow limitations of the setup, once the simulant is clumped up into the bag, there is a relatively small surface area through which the air can attempt to dry out the simulant. Second, the bag material itself could be limiting water transfer. A picture of the simulant in the PDMS bag and with the bag removed are shown in Figure 17 below where the gelatinous texture is apparent.

Figure 17. Fecal simulant in PDMS bag after running (Left) and once removed from the bag post processing (Right).

A second test was run with the PDMS bag and a wet paper towel once again, to try and isolate the issue to the bag material. A similar phenomenon occurred, and once again the test was cut short. These results can be seen in Table 18 and Table 19.

Table 18. PDMS and Paper Towel Testing Data.

Time (hr)	Inlet RH %	Inlet T (°C)	Outlet RH %	Outlet T (°C)	Bath Temp (°C)	P Vapor In (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0.25	4.16	38.5	6.19	25.0	-4.9	283	196	-10.1	-14.7	2.78
0.75	3.95	49.5	6.2	37.9	-4.2	476	409	-3.4	-5.4	1.77
1.25	3.86	50.2	5.75	40.5	-6.2	482	436	-3.2	-4.6	1.09
1.75	3.81	51.0	5.53	41.7	-5.9	494	447	-2.9	-4.2	1.17
2.25	3.8	50.4	5.47	41.2	-10	479	431	-3.3	-4.7	1.22
2.75	3.81	50.0	5.43	41.0	-9.7	471	423	-3.6	-5.0	1.22
3.25	4.25	49.5	6.09	40.6	-8.7	512	464	-2.4	-3.7	1.18

Table 19. PDMS and Paper Towel Testing Results.

Pre-Simulant + Bag Weight (g)	128.8
Post Simulant + Bag Weight (g)	126.2
Water Removed (g)	2.6
Water Collected (g)	0
% Retention	0.00%

These results can be compared with those from Table 14 and Table 15. Once again, relative humidity values were low, indicating a lack of water vapor in the air, and no water was collected. This conclusively pointed to the PDMS material as not being suitable for both water vapor permeability and liquid retention.

8.3.9 PTFE Bag Testing

The same test was completed with wet paper towels and a bag made from PTFE. Results of the testing are shown in Table 20 and Table 21.

Table 20. PTFE and Paper Towel Testing Data.

Time (hr)	Inlet RH %	Inlet T (°C)	Outlet RH %	Outlet T (°C)	Bath Temp (°C)	P Vapor In (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0.25	12.94	40.0	12.91	36.1	-7.9	956	772	6.3	3.3	6.13
0.75	16.79	49.5	20.82	41.7	-7.1	2023	1683	17.7	14.8	10.24
1.25	18.05	49.7	22.16	42.5	-6.4	2197	1868	19	16.4	9.80
1.75	18.97	48.1	23.75	40.5	-9.1	2124	1801	18.5	15.9	9.61
2.25	19.47	48.2	24.55	40.6	-8.6	2198	1872	19	16.5	9.67
2.75	19.08	49.3	23.5	42.1	-7.8	2276	1939	19.6	17.0	10.02
3.25	18.6	50.5	22.8	43.4	-6.9	2355	2014	20.1	17.6	10.10
3.25	18.5	50.5	22.52	43.5	-6.2	2343	2000	20	17.5	10.20

Table 21. PTFE and Paper Towel Testing Results.

Pre-Paper Towel + Bag Weight (g)	121.4
Post Paper Towel + Bag Weight (g)	90.2
Water Removed (g)	31.2
Water Collected (g)	16.6
% Retention	53.21%

Although the water removal rate was considerably slower with the bag than without it (as shown in Table 14), it was clear that the PTFE allowed for transfer of water vapor across the membrane.

For the remaining tests, the Sterlitech PTFE material would be used for the bags. In addition, a new type of simulant was mixed and tested, to hopefully eliminate water from being locked into the mixture. This mixture was made up of cocoa powder, peanut butter and DI water. The cocoa powder and peanut butter were maintained at a 1:1 ratio, with the water making up 75% simulant. Enough simulant was mixed to represent 1 bowel movement for 1 crewmember (108g). The results of the testing are shown in Table 22 and Table 23.

Table 22. PTFE and New Simulant Test Data.

Time (hr)	Inlet RH %	Inlet T (°C)	Outlet RH %	Outlet T (°C)	Bath Temp (°C)	P Vapor In (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0.25	27.17	38.8	34.8	31.3	-22.2	1882	1592	16.5	13.9	8.88
0.75	21.35	48.0	29.44	38.2	-22.1	2386	1974	20.3	17.3	12.05
1.25	18.25	50.0	23.59	41.4	-21.4	2254	1876	19.4	16.5	11.18
1.75	17.1	50.6	21.37	42.9	-20.9	2176	1839	18.8	16.2	9.97
2.25	16.26	50.8	20	43.4	-20	2090	1767	18.2	15.6	9.61
2.75	15.77	50.1	19.35	42.9	-19.1	1958	1665	17.2	14.6	8.70
3.25	15.05	50.5	18.55	43.2	-18.4	1906	1622	16.7	14.2	8.42
3.75	14.25	51.3	17.62	44.0	-17.8	1877	1606	16.5	14.1	7.98
4.25	13.38	51.0	16.49	43.9	-17.1	1737	1495	15.3	13.0	7.10
4.75	12.62	51.4	15.67	44.2	-16.4	1670	1443	14.7	12.4	6.64
5.25	11.7	51.0	14.6	43.7	-15.7	1519	1310	13.2	11.0	6.08
5.75	10.68	51.1	13.49	43.7	-15.1	1393	1210	11.9	9.8	5.26

Table 23. PTFE and New Simulant Test Results.

Pre-Simulant + Bag Weight (g)	117.4
Post Simulant + Bag Weight (g)	74.4
Water Removed (g)	43
% Water Removed	53.1%
Water Collected (g)	36.6
% Retention	85.12%
% Water Recovery	45.12%

The new bag material and simulant mixture combination allowed for slow water recovery. The test was stopped short of allowing the sample to fully dry, but it is apparent that with enough time, full water removal would have occurred. A photo of the bag after this run is shown in Figure 18 below.

Figure 18. PTFE bag with secondary fecal simulant post processing.

Over the almost 6 hours, 85% of the water removed was retained, which converts to an ultimate recovery of 45% of the water originally contained within the simulant. The water collected was frozen in the collection chamber as shown in Figure 19. Once again, the top rates of water removal were achieved within the first hour of testing, and slowly decreased. This is a positive trend, because if the drying rate can be amplified, most of the water removal will occur within the first few hours of the test, which is the ultimate goal of this testing.

Figure 19. Frozen collected water

8.3.10 Large Batch Testing

The true task for this system is to ultimately be able to dry 15-25 bags of simulant at a time. With a bag material selected, and water collection occurring, a test was run to determine how the test bed would fair when scaled up with more mass to dry. 15 simulant bags were made with sheets of PTFE and hot glue. The new simulant mixture of peanut butter, cocoa powder and DI water was mixed in a large batch and added to each bag for a total amount of 108 g of simulant. These bags were collectively placed in the test bench, numbered and ordered from 1 to 15, bottom to top, and the test was run. The test data and individual bag weights were recorded and are presented in Table 24 and Table 25.

Table 24. Large Batch Test Data.

Time (hr)	T Inlet (°C)	T Outlet (°C)	RH Inlet	RH Outlet	P Vapor in (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0.25	33.8	27.6	61.03	55.83	3210	2060	25.2	18.0	39.89
0.75	42.6	33.9	48.51	57.66	4116	3049	29.5	24.4	34.28
1.25	45.6	38.5	42.36	45.99	4188	3127	29.8	24.8	34.32
1.75	46.4	39.8	41.64	43.87	4298	3210	30.2	25.2	35.28
2.25	46.7	40.7	41.88	42.79	4374	3273	30.5	25.6	35.90
2.75	46.2	40.7	43.47	43.31	4445	3321	30.8	25.8	36.87
3.25	47.0	41.1	41.89	42.85	4447	3346	30.8	25.9	35.81
3.75	47.0	42.2	41.53	43.14	4422	3577	30.7	27.1	27.28
4.25	47.8	41.4	40.17	42.41	4452	3376	30.8	26.1	34.67
4.75	48.6	42.3	38.7	40.67	4467	3398	30.9	26.2	34.38
5.25	48.4	42.1	38.61	41.02	4400	3377	30.6	26.1	32.82
5.75	48.8	42.2	37.7	40.72	4394	3380	30.6	26.1	32.37
6.25	49.6	42.8	36.38	39.66	4399	3395	30.6	26.2	31.87
6.75	49.5	42.7	36.04	39.55	4336	3373	30.4	26.1	30.54
7.25	50.7	43.5	34.17	38.35	4360	3400	30.5	26.2	30.14
7.75	51.1	44.2	33.14	36.96	4329	3395	30.3	26.2	29.30
8.25	51.1	44.1	33.32	37.11	4343	3398	30.4	26.2	29.64
8.75	51.3	44.2	32.72	36.94	4300	3393	30.2	26.2	28.31

Table 25. Large Batch Bag Weights.

Bag #	Bag Weight (g)	Pre-Bag + Simulant (g)	Post Bag + Simulant (g)	Water Removed (g)
1	4.6	113.4	89.8	23.6
2	4.8	113.6	101.0	12.6
3	5	113.2	92.0	21.2
4	5	113	95.4	17.6
5	5.4	114	106.0	8.0
6	5.4	114	86.0	28.0
7	5.4	114	89.2	24.8
8	5.4	113.8	99.6	14.2
9	5.8	114	90.0	24.0
10	5	113.6	80.8	32.8
11	5	113.5	97.0	16.5
12	5	113.6	88.2	25.4
13	5.8	114.2	80.8	33.4
14	5.2	114	101.0	13.0
15	5.5	113.2	105.0	8.2
	Total:	1705.1	1401.8	303.3

After almost 9 hours, 25% of the water mass was removed (303.3 g). The water removal can be best visualized in Figure 20 as a difference between inlet and outlet water vapor partial pressure to the ionomer membrane. The difference between inlet and outlet water vapor pressure remained relatively constant over the 9 hours, indicating a constant water removal rate. By observing the temperature of the recirculating air, plotted on the same figure, it becomes clear that water availability in the recirculating air increased over time as temperature increased. Concurrently, water was being removed by the ionomer-membrane during the test. Both factors happening at the same time balanced out to maintain the constant water vapor partial pressure difference. This indicates that improving temperature of fecal samples will improve water removal rates and that the ionomer-membrane will keep up with the water load.

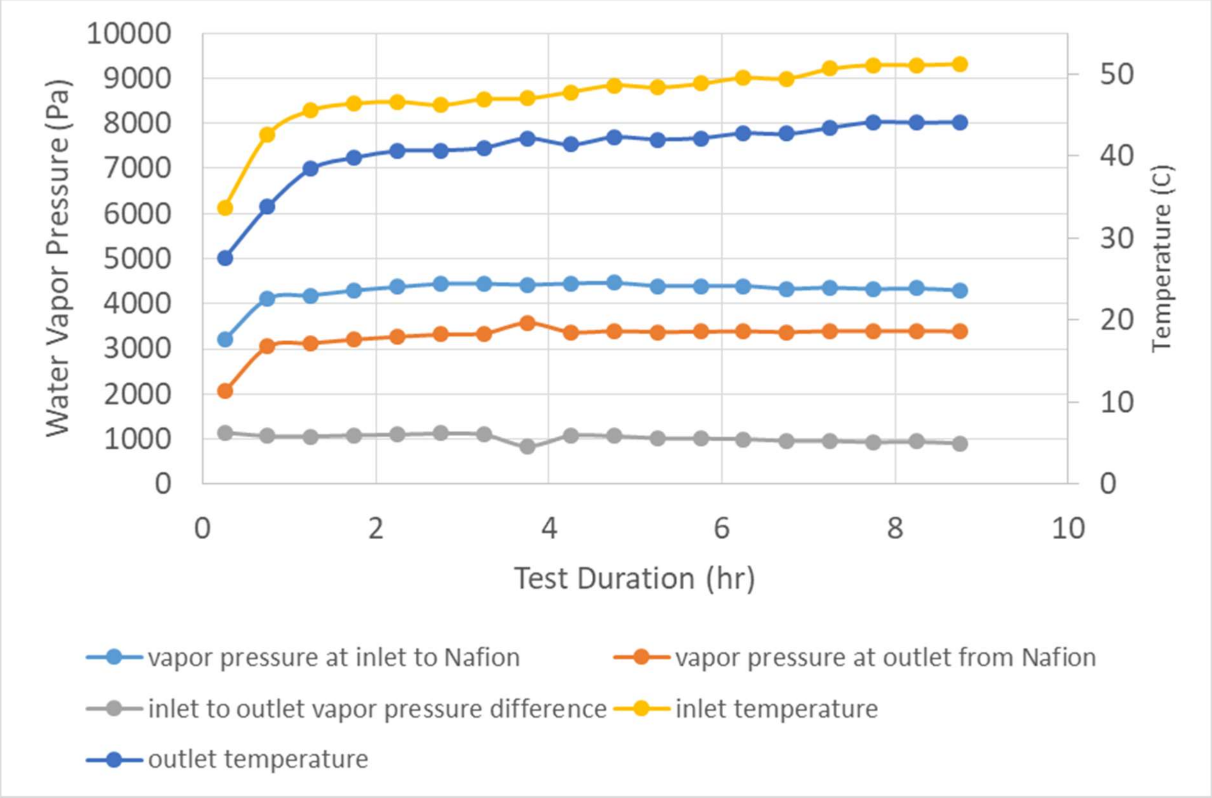


Figure 20. Large Batch Test – Water Vapor Pressure at the Inlet and Outlet to the ionomer-membrane Bundle, and the difference between them, and the Inlet and Outlet Temperature plotted vs. test duration

8.3.11 Completion Testing

A final test was run in an effort to bring one sample to its fully dehydrated state. The same conditions applied in the large batch test were used, and the final test bench configuration is shown in Figure 21. The results are shown in Table 26 and Table 27. It can be seen in Table 27 that 87% of the water was removed from the sample over 7 hours and 15 minutes, with 83% of that removed water being collected in the cold trap. This testing demonstrates that >80% water removal can be achieved from a simulant fecal matter held in a PTFE bag using an ionomer-membrane water filtration process.

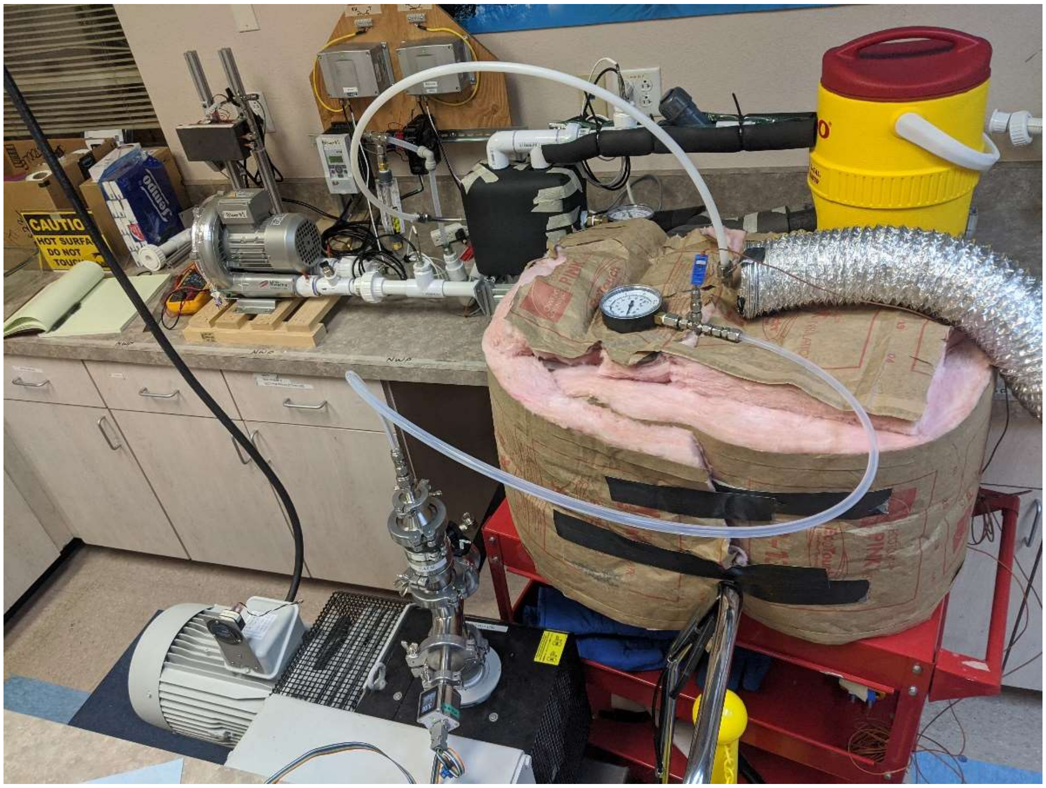


Figure 21. Final test bench configuration.

Table 26. PTFE with New Simulant Completion Data.

Time (hr)	T Inlet (°C)	T Outlet (°C)	RH Inlet	RH Outlet	P Vapor in (Pa)	P Vapor Out (Pa)	T Dew In (°C)	T Dew Out (°C)	Water Removal Rate (g/hr)
0.25	44.7	33.0	27.99	42.27	2647	2134	22.0	18.5	15.01
0.75	53.1	41.4	21.37	31.11	3074	2477	24.5	20.9	17.10
1.25	55.2	44.9	19.22	26	3054	2480	24.4	21.0	16.60
1.75	56.0	46.4	18.3	23.98	3022	2471	24.2	20.9	16.02
2.25	56.0	46.9	17.77	22.88	2938	2421	23.7	20.6	15.04
2.75	55.5	46.6	17.45	22.45	2822	2336	23.1	20.0	14.12
3.25	55.4	46.4	16.86	21.86	2710	2258	22.4	19.4	13.09
3.75	56.3	47.2	15.79	20.64	2644	2215	22.0	19.1	12.27
4.25	56.4	47.3	14.4	19.01	2429	2047	20.6	17.9	10.87
4.75	56.7	47.4	13.2	17.63	2258	1914	19.4	16.8	9.68
5.25	58.0	48.6	11.68	15.72	2120	1812	18.4	15.9	8.52
5.75	58.0	48.6	10.29	13.96	1871	1605	16.5	14.1	7.30
6.25	57.7	48.2	9.21	12.6	1649	1425	14.5	12.2	6.08
6.75	57.6	48.1	8.21	11.37	1467	1277	12.7	10.6	5.05
7.25	58.8	49.2	7.2	10.07	1360	1193	11.5	9.6	4.37

Table 27. PTFE with New Simulant Completion Results.

Pre-Simulant + Bag Weight (g)	116.2
Post Simulant + Bag Weight (g)	45.6
Water Removed (g)	70.6
% Water Removed	87.16%
Water Collected (g)	58.7
% Water Collected	83.14%

The water removal can again be visualized in Figure 22 as a difference between inlet and outlet water vapor partial pressure to the ionomer-membrane membrane with the temperature at the inlet and outlet also plotted. In the completion test, the temperature was controlled to a higher value and reached that temperature faster due to the lower thermal mass of a single bag compared with the large batch testing.

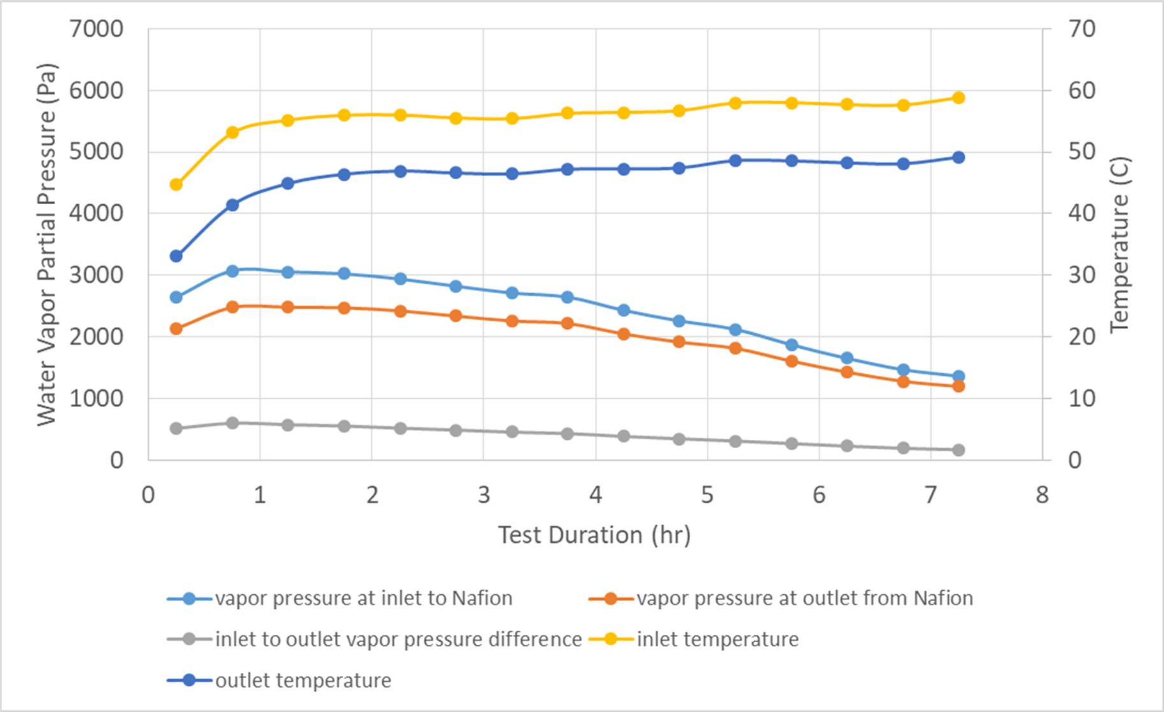


Figure 22. Completion Test – Water Vapor Pressure at the Inlet and Outlet to the ionomer-membrane Bundle, and the difference between them, and the Inlet and Outlet Temperature plotted vs. Test Duration

The water recovery rate and total water collected are shown together in Figure 23. The peak of the water removal rate is apparent which occurs within the first hour of the process. In the worst-case scenario, there would be a possible 25 bags in 2 days which equates to roughly 1 bag every 2 hrs. This allows for the greatest recovery rates to take place before multiple bags are stacked which may inhibit ideal air flow. It should be noted that the total water recovered is based on the recovery rates and no actual data was collected throughout the test. Rather, the mass was taken at the beginning and conclusion of the test. The total water recovered behaves as expected where it will eventually asymptote at a point corresponding to the available water and where the recovery rate diminishes.

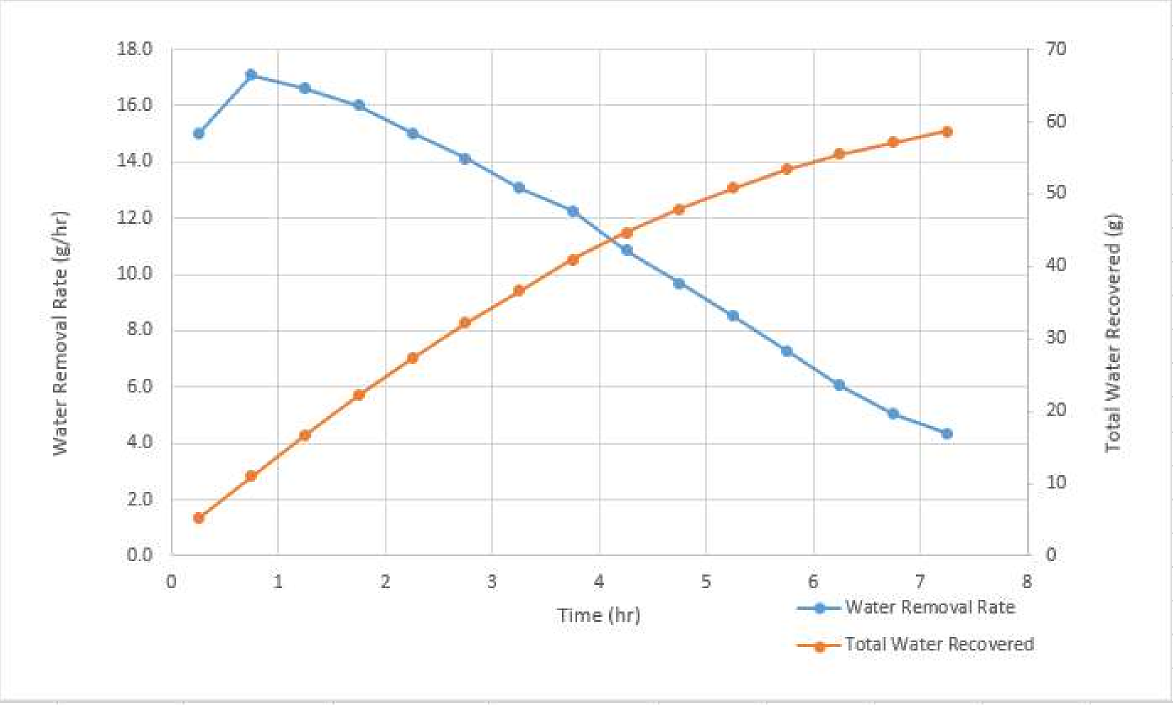


Figure 23. Completion Test – Water Removal Rate and Total Water Collected plotted vs. Test Duration

The results of the testing from the Large Batch Test and the Completion Test demonstrate proof of concept and design feasibility. With even the preliminary testbed equipment which was not optimized in any way for STOOLE performance, the system exceeded the water recovery requirements and stayed in bounds of all other requirements. The water activity level, being the exception, requires increased thermal performance fidelity.

9 VERIFICATION AND VALIDATION OF REQUIREMENTS

9.1 Verification Results

The conclusion of the above testing clearly demonstrates the following verification and validation of requirements.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Water Recovery	FUNC-1	The system shall recover a minimum of 80% of water by mass from human metabolic waste.	**Test:** Verification is considered successful when a laboratory test utilizing fecal simulant confirms 80% water recovery by mass.	Test: Laboratory benchtop testing confirmed preliminary water recover of 87% without specialized optimization.
Water Activity Level	FUNC-2	The system shall obtain a water activity level of less than 0.6.	**Test:** Verification is considered successful when closed sample chamber testing confirms an activity level of less than 0.6.	Test: A_w was measured before dehydration level at 0.94. After drying to 87% the A_w is 0.74.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Operating Temperature	FUNC-3	The system should operate using temperatures no greater than 110C.	**Analysis:** Verification is considered successful when analysis of system design confirms no operation which exceed 110C.	Analysis: The maximum temperature utilized in the system was 58.8°C.
Lifetime	FUNC-4	STOOLE should require replacement no more often than once every 18 months.	**Analysis:** Verification is considered successful when analysis of vendor CofC and design components confirm system lifetime is at least 18 months.	Analysis: TBD. Major design components are still under development.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Dormancy	FUNC-5	STOOLE should meet all functional requirements after a dormancy period of up to 18 months.	**Analysis:** Verification is considered successful when analysis of vendor CofC and analysis of design components confirm operation after 18-month dormancy.	Analysis: TBD. Major design components are still under development.
Drying Time	FUNC-6	STOOLE shall be capable of drying 15-25 fecal deposits (of 75% water by mass) within [TBD] hours.	**Test:** Verification is considered successful when fecal drying test data confirms drying time is within TBD hours.	Test: Preliminary proof of concept benchtop testing extrapolates to a drying time of 52 hours.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Material Compatibility	FUNC-7	All wetted components in the STOOLE system shall be compatible with human metabolic waste per [TBD].	**Analysis:** Verification will be considered successful when analysis of the Master Equipment List (MEL) confirms that wetted components are compatible with human metabolic waste using previous test data, historical use, and material specifications.	Analysis: Wetted components were compatible with fecal simulant. Further compatibility requirements are planned in the event of a Phase II award.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Gravity Environment	ENV-1	The system shall be capable of meeting all functional requirements in microgravity, Lunar surface operation or Martian planetary surface operation.	**Analysis:** Verification is considered successful when analysis of design confirms functionality in microgravity, Lunar surface operations, and Martian planetary surface operations.	Analysis: Gravity conditions for Phase I setup is considered the most conservative test approach. Functional requirements are not limited by a microgravity environment.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Environmental Temperature	ENV-2	STOOLE shall meet all functional requirements when exposed to the ISS atmosphere temperatures ranging from 5°C to 45°C (41°F to 113°F)	**Analysis:** Verification is considered successful when analysis of vendor specifications and design tolerances confirm functionality in environmental temperature range.	Analysis: All materials have temperature ranges beyond bounding limits of ISS atmosphere.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Vented Constituents	INT-1	STOOLE effluent gas stream trace component concentrations, while recovering water from the human metabolic waste, shall comply with 180-day Spacecraft Maximum Allowable Concentrations (SMACs), found in SSP 41000, Revision CF, Table VIII.	**Test:** Verification is considered successful when effluent water quality is tested and is compliance with the 180-day SMACs.	Test: TBD. SMAC and vented constituents testing were not proposed for Phase I. Planned for Phase II testing.

Rqmt Name	Rqmt #	Requirement	Verification Methods	Verification Result
Reusability	INT-2	STOOLE shall ensure reusability of the UWMS canister	**Analysis:** Verification is considered successful when analysis confirms material compatibility with the UWMS canister.	Analysis: The UWMS canister in the Phase I ConOps is designed to be reusable. Phase I canister compatible with fecal simulant.
Interface	INT-3	STOOLE should interface with the [TBD] UWMS features.	**Inspection:** Inspection of NASA drawings which define the ISS interfaces and inspection of assembly drawings which confirm matability.	Inspection: TBD. Interfaces were not able to be procured due to Intellectual Property. Further development needed in Phase II.

10 CONCEPTUAL DESIGN

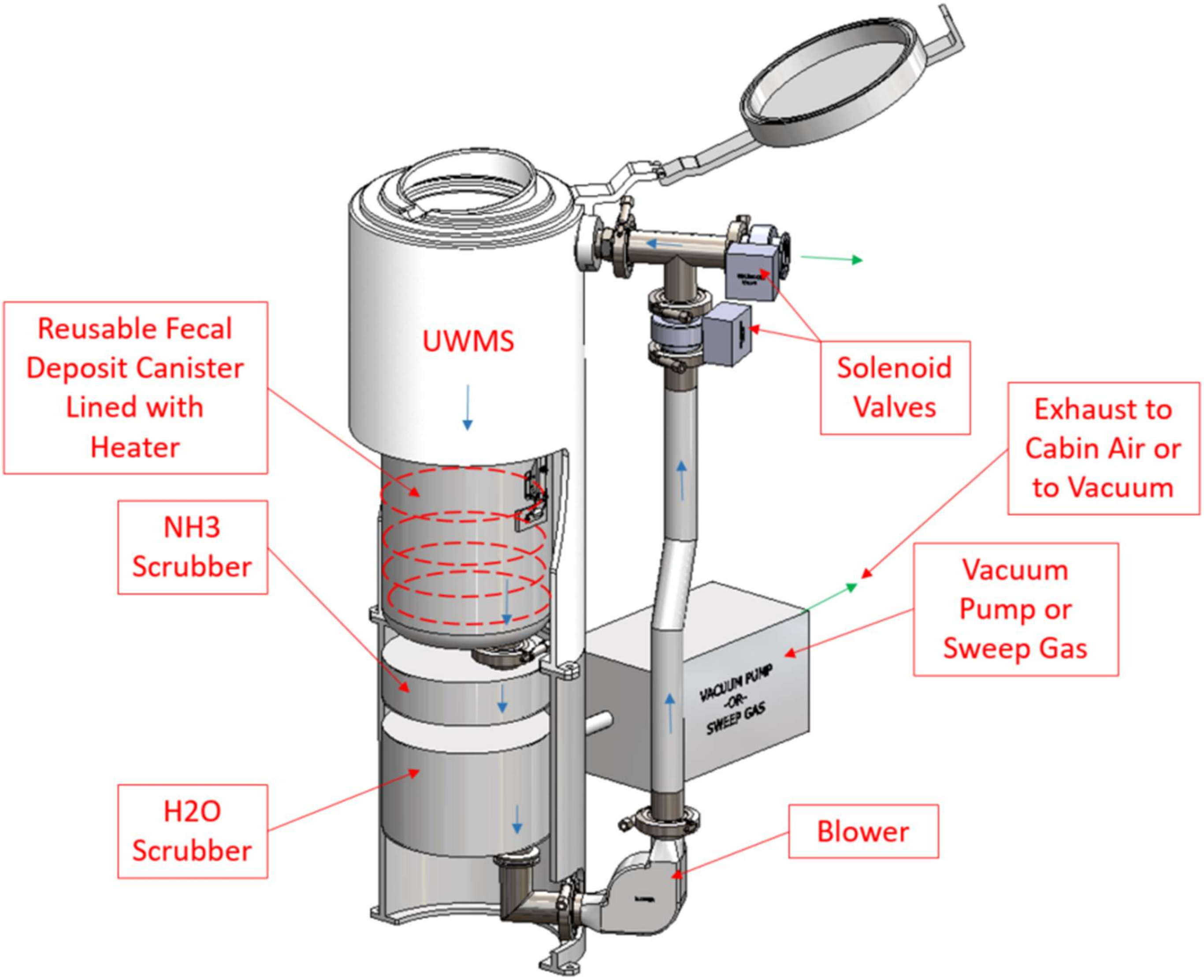
The system-level design solution for the STOOLE functional prototype is developed here and intends to conceptually capture the integration of the STOOLE technology to the current UWMS system. In order to do this, key lessons that were learned from testing will be implemented. The STOOLE testbed will be optimized for parameters such as flow rates, temperatures, pressures, and materials. The STOOLE system will be compacted in size such that it could be incorporated to the UWMS with minimal spatial impact (or designed as a standalone assembly). One important factor in the conceptual design is the ability to retain the waste storage containers as a reusable item. This would greatly reduce the need for supplying fecal canisters to the ISS as it is currently employed. Below, in Figure 24, is the conceptual design package that has been integrated with the UWMS. The STOOLE technology is not limited to the integration in the current system, however. The system could be relocated to adjacent space or be rearranged as a standalone system. In the latter scenario, this could facilitate the integration with MIS to streamline the transfer of dried fecal deposit bags for 3D printing operations.

The STOOLE team will assess modifying the current canisters that are used for fecal deposits. The bottom of these canisters would be modified to adapt to the ammonia scrubber, which is necessary for the use of the ionomer membrane technology in the following canister. These two canisters are mated with KF flange fittings making any planned maintenance easy and accessible. This also allows for the removal of the fecal canister for swapping out once fully loaded. The inside of the canister will be lined with a heater source that is intended to heat the samples and air as it passes through. This is indicated by dashed red lines in the figure below. The heater source could potentially include an antimicrobial aspect which would prevent bacterial growth while STOOLE is processing. Current testing has been utilizing 70°C air, but future work will optimize this temperature as heat will induce stronger odors.

The ammonia scrubber can be made of a few known methods of removal to include but not limited to an acid bubbler or impregnated carbon filter. Alternatively, an innovative design could be developed. Once through the ammonia scrubber, the air will pass through the ionomer membranes. These membranes can either be tube and shell or flat sheet membranes. The down-selection of this material form will depend on the surface area which allows the process to take place within a given time constraint. In either case, a sweep gas or vacuum pump will pull the processed water vapor and release it to the surrounding cabin air. As an alternate operation of the system, valving can be implemented to direct the flow of humidified air straight to the vacuum of space.

A blower will be the driving force behind the air circulation in the STOOLE system. This pushes air up through where STOOLE will tap into the existing fan system, depicted below with a tee connection. The existing fan system is engaged when the lid is opened to assist the removal of fecal matter from the astronauts by providing suction. In order to accommodate this feature, a set of solenoids (or similar) valves will be engaged when the lid is opened, closing the STOOLE circulation loop and opening the fan suction. Once the seat is close, they will engage in the reverse direction allowing the circulation of air over the newly deposited bag. The STOOLE system air flow pathway is indicated by blue arrows and the green arrows indicate the suction flow pathway and clean water vapor pathway from the vacuum pump.

Figure 24. STOOLE conceptual design for Phase II integrated with next generation UWMS



Optionally, to incorporate the on-orbit upcycling approach, the MIS Recycler-Printer would be loaded with dried material from the STOOLE system. The material would be fed into a shredding subsystem capable of reducing it to particle sizes suitable for the system's extruder. The shredded materials would be passed into a compounding subsystem and combined with a pre-determined mass ratio of plastic feedstock, then heated and mixed to achieve compound homogeneity. The compound would then be passed into the extruder for deposition in the form of the final product.

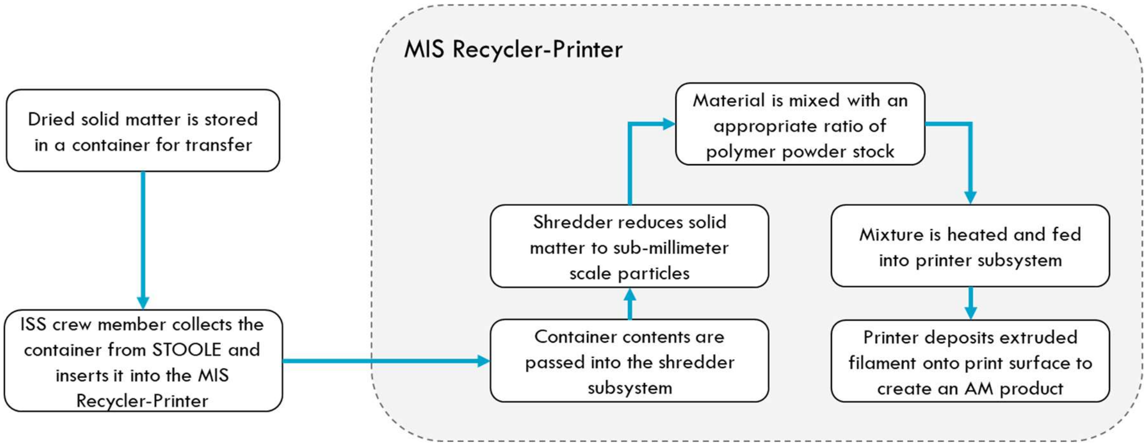


Figure 25. Concept of Operations for an on-station MIS Recycler-Printer utilizing STOOLE dried matter

11 CONCLUSIONS AND FUTURE WORK

11.1 Discussion

The development testing yielded impressive results. The key conclusions of this phase are collected here:

Greater than 80% water removal can be achieved from simulant fecal matter held in a PTFE bag using an ionomer-membrane water filtration process. This can be maximized by increasing the temperature of the heated air flow, to improve the partial pressure differential across the ionomer-membrane.

Even at the relatively low temperatures used in this testing, drying of a full batch of 15-25 bags of simulant can occur under 3 days. Air flow around simulant bags should be optimized to interact with the largest bag surface area possible.

PTFE bags allowed for the best drying rates of the simulant. Pore size should be optimized to allow for the best water removal rates possible.

Water activity level was reduced by 21% (from 0.94 to 0.74) and a path forward for optimization of the system will increase fidelity of the thermal performance to yield even lower water activity levels.

11.2 Future Work

Future work is slated to include testing with actual human feces, development of a stand-alone assembly, upgraded downselect of fecal simulant, and a full-scale thermodynamic model for optimization of thermal and power parameters.

REFERENCES

1. Eckart, Peter. *Spaceflight Life Support and Biospherics*. Springer, 2011.
2. Image is courtesy of the Greater Vancouver Regional District through the United States Geological Survey.
3. "THE PRIMARY TREATMENT PROCESS." *Science for a Changing World*, The United States Geological Survey, www.usgs.gov/special-topic/water-science-school/science/a-visit-a-wastewater-treatment-plant?qt-science_center_objects=0#qt-science_center_objects.
4. "ADVANTAGES OF BIOLOGICAL WASTEWATER TREATMENTS." *Aerobic Digestion Reactors (ADR) for Biological Wastewater Treatment*, Condorchem Envitech, 20 Feb. 2017, blog-en.condorchem.com/aerobic-reactors-for-biological-wastewater-treatment/#.YGuU9K9KiiM.
5. C. Visvanathan , R. Ben Aim & K. Parameshwaran (2000) Membrane Separation Bioreactors for Wastewater Treatment, Critical Reviews in Environmental Science and Technology, 30:1, 1-48, DOI: 10.1080/10643380091184165
6. Encyclopedia of Chemical Engineering: Chimneys, www.encyclopedia.che.engin.umich.edu/Pages/EnergyTransfer/Chimneys/Chimneys.html
7. Wiśniewski D, Gołaszewski J. Thermal treatment of dewatered digestate for energy use. In: International Anaerobic Digestion Symposium at Biogas World; 23-25.04.2013, Berlin, Germany; 2013.
8. Poudel J, Ohm T, Lee SH, Oh SC. A study on torrefaction of sewage sludge to enhance solid fuel qualities. Waste Management. 2015;40:112-118. DOI: 10.1016/j.wasman.2015.03.012
9. Hollins, Hunter. "Forgotten Hardware: How to Urinate in a Spacesuit." *Advances in Physiology Education*, vol. 37, no. 2, 2013, pp. 123–128.
10. Sauer, R.L.; and Bustamante, R.D.: *Water Supply and Waste Management in Spacecraft-Past, Present, & Future.* Paper presented at the Twenty-Sixth Purdue Industrial Waste Conference (Lafayette, Indiana), May 4-6,1971.
11. Johnston, Richard S, and Lawrence F Dietlein, editors. *Biomedical Results from Skylab*. Scientific and Technical Information Office, 1977.
12. "Gigapan: Space Shuttle Discovery Toilet". National Geographic. National Geographic Society. September 5, 2013.
13. Thomas J. Stapleton; Shelley Baccus; James L. Broyan Jr. (January 1, 2013). "Development of a Universal Waste Management System". NASA.
14. Sargusignh, Miriam et. al. "48th International Conference on Environmental Systems." *NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2017 to 2018 Overview*.
15. Wignarajah, Kanapathipillai, et. al. "Simulated Human Feces for Testing Human Waste Processing Technologies in Space Systems." *International Conference on Environmental Systems*, 2006.
16. Wignarajah, Kanapathipillai, et. al. "Evaluation of the Microwave Enhanced Freeze Drying Technology for Processing Solid Wastes" *International Conference on Environmental Systems*, 2008.