Evolution of the Next Exploration Toilet through Human-in-the-Loop (HITL) Testing

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Human waste collection in space is a unique and necessary function that all crewmembers must perform. The variability in how each crewmember uses the toilet to urinate and defecate introduces complexities and challenges with regards to overall hardware design. Because of this variability, it is important to consider crew inputs in all aspects of a toilet design especially with regards to crew interfaces that could impact overall waste collection. Access to crew feedback is essential to the design process and should be considered early and often through the various design phases. In 2020, NASA started a project for the Human Landing System (HLS) program to develop a Government Furnished Equipment (GFE) toilet option. The project is known as the Lavatory On-Orbit (LOO). During the early development of the LOO, the project team conducted several crew evaluations to collect and summarize valuable crew feedback on system design, function, and overall usability to influence the next design iteration. Because every person could use the system differently in space, it was extremely important to collect and analyze the data in a very methodical manner to appropriately influence the design based on the evaluation results. Establishing a standard process ensures consistent data collection from one evaluation to another, helps to maintain privacy for each test subject's inputs and removes any potential bias from test subject to test subject. To date, the team has completed four rounds of crew evaluations with multiple crewmembers on prototypes for the different LOO subsystems. This paper will summarize the methodology used to conduct the evaluations as well as how data was collected and analyzed. The paper will also provide details on each of the evaluations and how the design was updated based on the results.

Nomenclature

AB	=	Artemis Bag
ACY	=	Russian Waste Management System (Russian acronym)
BUS	=	Backup Urine Systems
CCU	=	Collapsible Contingency Urinal
EDO	=	Extended Duration Orbiter

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GFE	=	Government Furnished Equipment
HITL	=	Human-in-the-Loop
HLS	=	Human Landing System
ISS	=	International Space Station
JSC	=	Johnson Space Center
LOO	=	Lavatory On-Orbit
QD	=	Quick Disconnect
RWB	=	Removable Waste Bag
SRR	=	System Requirements Review
TRR	=	Test Readiness Review
UWMS	=	Universal Waste Management System
WCS	=	Waste Collector System
WHC	=	Waste and Hygiene Compartment

I. Introduction

WASTE Management Systems (WMSs) are crucial to successful human spaceflight. Every single crew member will interface with the system during the mission and each person will use it differently based on anatomical differences as well as previous experience with other waste collection systems. This makes the design of the crew interfaces a unique challenge. The project team at NASA's Johnson Space Center (JSC) developing a WMS for the upcoming missions to the lunar surface is in a unique position to communicate with current astronauts and have their feedback influence the design early in the design phase. Using a WMS during spaceflight is an experience that only flown astronauts have and their inputs are critical to the efficacy of new designs. The use of crew evaluations, or Human-In-The-Loop (HITL) Testing, has become the preferred method of obtaining feedback on hardware prototypes throughout the design phase in a consistent, unbiased, and candid way from the end users themselves. Feedback on crew interfaces is especially important to collect during these evaluations so the hardware can be designed to accommodate as many user's preferences as possible.

II. History of Space Toilets

Historically, waste collection in the early years of the space program provided basic and simple collection options that were designed to support male crew only. Typically, the collection systems required intimate contact with the body. For the Mercury flights, a roll-on cuff was donned to collect urine. The crew avoided defecation during the Mercury flights by having a low solids residual diet prior to the flight.

During the Gemini and Apollo programs, urine was also collected via a roll-on cuff that was connected to a collection bag or captured in a small hand-held honeycomb cylinder before venting overboard. For defecation, the crew used individual bags that were attached to the body via an adhesive (Figure 1). Once used, the bags were removed from the body and a germicidal agent was added into the bag and manually kneaded into the feces for stabilization. The bag was then sealed, rolled up and stored. The bags did not provide any means of odor control which greatly impacted the odor in the vehicle. To avoid defecating during the mission, some crew even continued with the low solids residual diet during the flight. This was primarily due to the dislike of using the individual fecal collection bags and overall process for collection.

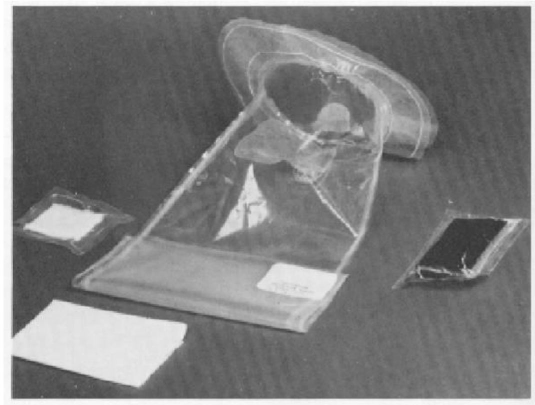


Figure 1. Apollo Bag and ancillary hardware used during Gemini and Apollo programs for fecal collection.

In general, these collection methods were unfavorable with the crew since they experienced frequent waste escapes[1].

Since those early programs, waste collection has improved considerably with regards to overall waste capture, hygiene and providing crew interfaces to accommodate both male and female crew. One significant improvement is the addition of airflow. Without gravity, airflow is needed to assist in waste separation and retention once it exits the body as well as provide odor control during use. Airflow was first introduced for waste collection during the Skylab flights, with waste collected and stored for medical evaluation. Urine was collected via a hose and funnel configuration and the airflow helped to entrain the urine in the system. The urine was separated from the air via rotary separators and collected into individual bags. A deployable seat with airflow was used for fecal collection into individual bags[1].

Since Skylab, all US and Russian developed waste collection systems have relied on similar design and methods for waste collection including continuing to rely on airflow for capture and odor control. The Extended Duration Orbiter (EDO) Waste Collector System (WCS) developed in the early 1990s, introduced removable and replaceable fecal canisters as well as the use of individual fecal bags and fecal compaction. Its predecessor, the Shuttle WCS collected fecal waste into a fixed tank without individual bags. In addition, the EDO commode seat opening was increased and included features to assist with alignment during use. The Russian toilets on Soyuz and ISS (in the Russian Service Module) use similar methodologies for collection but provide a smaller seat opening and smaller volume fecal bag. The Waste and Hygiene Compartment (WHC) in Node 3 was developed to support the ISS expansion of the crew to six and has the same components as the Russian system (ACY) in the Service Module but packaged to fit into an ISS rack[2].

The Universal Waste Management System (UWMS) was recently developed for use on longer duration missions with a focus on minimizing overall system mass and volume as well as improving on crew hygiene and interfaces[3,4]. The UWMS is similar to previous systems in capture methods for urine (hose and funnel) and fecal waste (individual bags). Improvements to the crew interfaces have included seat and funnel redesign to help with body and hardware alignment specifically to aid female crew during simultaneous urination and defecation.

The initial UWMS design was developed for both the Orion Artemis-2 mission as well as to complete an ISS technology demonstration. The Orion unit was delivered in 2019 and installed in the Artemis-2 vehicle. The ISS unit was delivered in June 2020 and launched to ISS later that year with plans for completing the ISS demonstration in 2023[4].

III. Lavatory On-Orbit (LOO) Hardware

A. Overview

In July 2020, development of the Lavatory On-Orbit (LOO) project was started to support the Human Landing System (HLS) program initial lunar mission. Since 2020, the project has completed detailed requirements development and review and is currently in its preliminary design phase including completing its Preliminary Design Review (PDR) in January 2023. The hardware overview details provided below describe the preliminary design since the design is yet to be completed.

The LOO hardware provides accommodations for the collection, containment, and disposal of body waste (urine, feces, diarrhea, menses, and vomit) for both male and female crewmembers as well as any consumables used during operations like wipes, gloves, and feminine hygiene products. The LOO hardware consists of three major elements –

1) a primary waste collection system for both urination and defecation called the “Toilet Assembly”, 2) an alternate/backup fecal collection system called the “Artemis Bag” (AB) and 3) an alternate/backup urine collection system called the “Backup Urine System” (BUS) (Figure 2).

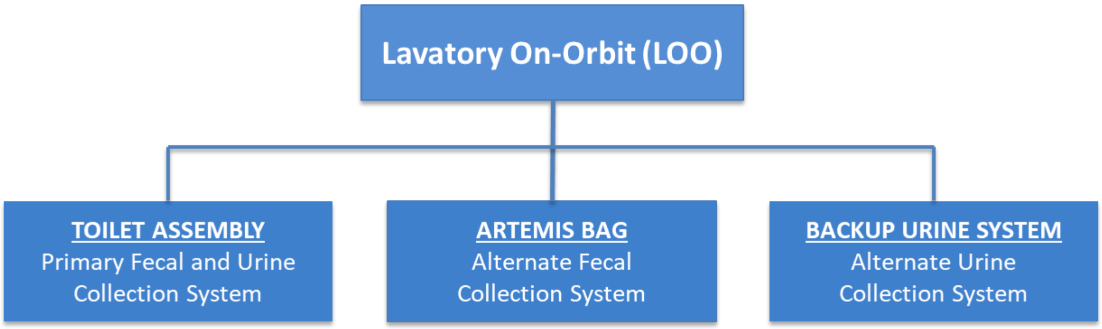


Figure 2. LOO hardware consists of 3 major elements – the Toilet Assembly, Artemis Bag (AB), and Backup Urine System (BUS).

The hardware is designed to operate in both microgravity and partial gravity to support waste management activities during lunar descent, ascent, and lunar surface operations. The alternate waste collection systems will be used in the event of a Toilet Assembly failure or if the system is left on the lunar surface prior to lunar ascent. The LOO hardware also supports simultaneous operations (defecation and urination at the same time) with either the primary system, alternate systems, or a combination of primary and alternate systems.

While still early in its design, the project has identified some key driving requirements that will still need to be considered as the design matures. As mentioned above, the system will operate in both microgravity and lunar gravity environments which has driven the overall system architecture and design. Partial gravity should assist with overall waste collection and waste separation from the body; however, the system will need to provide adequate features in microgravity for these same operations which could drive overall complexity of the system including crew interfaces. Since the system will be operated during the lunar surface stay, it is likely that it will be exposed to lunar dust that may enter the cabin. Lunar dust compatibility from an overall materials selection and component performance will need to be considered. In addition, the system will be exposed to a higher oxygen concentration environment (34% O_2 at 8.2 psia) which can also impact materials selection and overall system performance. The LOO hardware may also need to be compatible to vacuum exposure in the event of any space walks (if the vehicle is used as an airlock) or if the hardware is disposed of on the lunar surface. Other key drivers to the design include minimizing overall mass and volume as well as minimizing noise during use.

B. System Architecture

1. Toilet Assembly

The LOO Toilet Assembly is the primary system for both urine and fecal collection. The fecal collection system consists of a structure with a lid and a seat (see Figure 3). The seat is the primary crew interface for fecal collection. A single-use fecal bag is used to collect and contain the fecal deposit and any consumables used to clean the user or hardware. The fecal bag is attached over the seat to protect any surfaces that come in contact with the user from potential fouling. Once used, the fecal bag is sealed and dropped into a larger bag that holds approximately 13 deposits. The larger bag, known as the Removable Waste Bag (RWB), can be easily changed out when full and put into an odor control bag for disposal. To assist with waste separation and containment, the system provides airflow via a fan which is powered on via a microswitch when the seat lid is opened. The system also includes a filter in line with the fan to provide odor control while the system is in use.

For urine collection, urine is collected via a urine hose and funnel. Airflow is provided on the urine collection system side to aid in drawing the urine away from the body and to also help with odor control during use. Airflow on the urine side is provided also via a microswitch that activates the system when the urine hose is removed from the cradle (see Figure 3). The urine and air are then passed through a passive separator that separates the air from the urine before exhausting the air to the cabin. Prior to exhausting to the cabin, the air passes through an odor filter. Once the air is removed from the urine, the urine is stored in a soft bladder that is connected to the structure via a Quick Disconnect (QD). The bladder is sized to hold approximately 6L of urine and would be changed out once a day assuming two crew and six urinations per crew per day. The system will provide a method to microbially stabilize

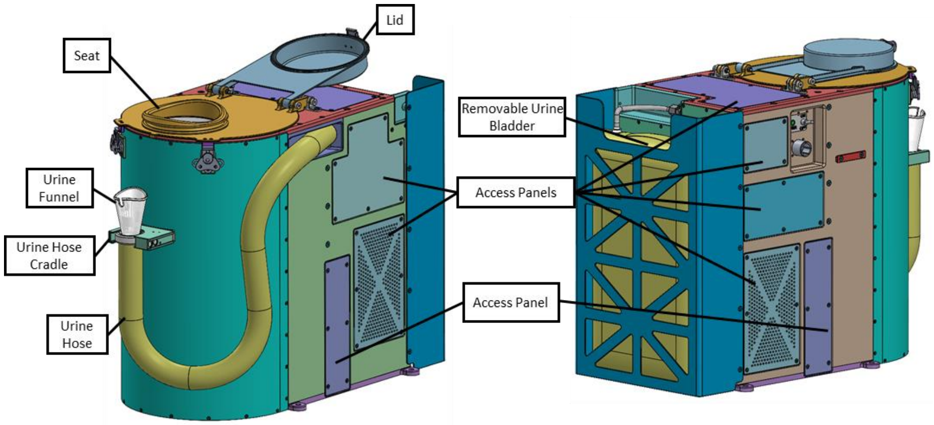


Figure 3. LOO Toilet Assembly preliminary CAD model showing exterior features including primary crew interfaces.

the urine although at this time the stabilization method is still unknown since the design is still preliminary.

2. Artemis Bag (AB)

The Artemis Bag is a passive fecal collection system based on the Apollo Bag design (Figure 1) with several improvements. As mentioned previously, the Apollo Bag was not favorable to the crew since it was deemed unhygienic, odorous and time consuming. In addition, the Apollo Bag was not sized to support female anatomy. The concept for the Artemis Bag is to improve on the Apollo Bag specifically in the areas of collection, containment, and crew interfaces. The Artemis Bag consists of a seat interface and bag to collect and contain feces and consumables when the primary system is not available. The seat provides hand holds to allow the crewmember to position the seat/bag as needed for use. The bag is a one-time use bag that attaches over the seat via an elastic (similar to the fecal bag for the Toilet Assembly) to reduce any potential fouling of the seat. The seat is reusable and could be hand-held or mounted to a wall or structure to allow for hands-free use. The Artemis Bag also provides an aid to assist in initial fecal separation although the design is yet to be finalized (Figure 4 shows a hand wipe option for fecal separation).

Figure 4. Artemis Bag with "wipe" feature to aid in initial fecal separation. Evaluated during evaluation #4.

After use, the bag is removed from the seat, closed via a drawstring closure, and then placed in a secondary odor control bag for storage.

3. Backup Urine System (BUS)

The Backup Urine System is the alternate urine collection system if the primary collection system on Toilet Assembly is not available or has failed. The baseline design for BUS is based on the Orion developed Collapsible Contingency Urinal (CCU) hardware (Figure 5). The system was developed as a backup urine collection system in the event of a failure of the Universal Waste Management System (UWMS) on the Orion vehicle[4]. The system is a passive hand-held device that includes a crew interface and a bag to collect urine. The system relies on capillary action along with hydrophobic and hydrophilic materials to draw the urine away from the body and down to the bottom of the attached bag. There are two versions of the CCU – a male and female version – with the difference being an additional crew interface for female use. The technology has been proven to work in 1-G and microgravity environments through ground testing and technology demonstrations aboard the ISS[4].

Figure 5. High-fidelity prototype of the Collapsible Contingency Urinal (CCU) hardware (with male interface).

The CCU design was evaluated for HLS use during crew evaluation #4 discussed below. Overall, the crew did find the CCU design acceptable; however, there are some significant differences between the BUS requirements and the CCU as-designed hardware that the project will need to consider going forward into the next design iteration. As mentioned above, lunar dust and the higher O2 concentration could influence material compatibility. In addition, the BUS will need to provide urine stabilization which may also impact materials and system performance. Menses collection and odor control will need to be considered since CCU does not currently meet these requirements. Urine disposal operations will also need to be determined (venting vs. stowing) as the design matures.

IV. Methodology for Human-in-the-Loop (HITL) Testing (Crew Evaluations)

A. Evaluation Process and Structure

The first step in conducting successful crew evaluations to influence the hardware design, is to establish a standard process to ensure consistent data collection and analysis, maintain crew privacy and remove any potential bias from test subject to test subject. To accomplish this, the team established a crew evaluation process memo. The memo documents the steps and coordination needed with various stakeholders across the HLS program and JSC to conduct the evaluations and capture the data for each of the test subjects. It captures specific details on 1) how to request JSC Crew Office participation as test subjects, 2) process and approvals for any safety-related reviews, 3) how the evaluations will be conducted and 4) how data will be documented, collected, and analyzed. As part of the iterative hardware-design process, the HLS LOO project team also identified the timeframe needed for each Crew HITL/evaluation to support the preliminary and critical hardware-design phases and included those dates in the planning schedule for each evaluation. This provided a basis for establishing the evaluation process and the amount of time needed for planning, documentation development, safety reviews, test setup and finally performing the evaluations.

A very critical step of the process includes completing a formal safety review known as a Test Readiness Review (TRR) prior to the first evaluation. The review formally documents the objectives of the evaluations and verifies that safety protocols are in place to prevent any injuries or hardware failures during the evaluations. In addition, a safety walk-through of the facility where the evaluations will take place and an inspection of the prototype hardware to be used is performed with several project stakeholders. This allows for real-time feedback on potential hazards that need correcting prior to the evaluations. A final dry run is conducted within one to two days of the first scheduled evaluation.

Each evaluation follows a similar script in which the test subjects are given a pre-brief covering the purpose/goals of the evaluation, any known safety concerns, hardware overview, evaluation flow, questionnaire, and requests for open and ample feedback. Each test subject is assigned a dedicated Test Conductor that will “interview” the test subject based on the questionnaire and record their responses. To provide as much privacy as possible, the evaluations are only attended by project personnel and a limited number of project stakeholders.

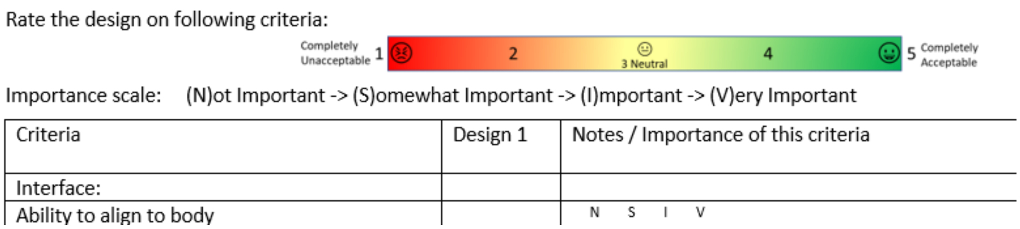
B. Data Capture and Analysis

1. Questionnaire Development

For each evaluation, a questionnaire is developed by the project to collect inputs from each test subject. This serves as the primary data collection tool and the outline for the flow of each crew evaluation. The questionnaire is meant to take each test subject through the function of each piece of hardware in a sequence matching the standard operations with the toilet and allow the test subject to provide input on overall usability, functionality and basically what works and what does not work for the operations.

The questionnaires consist of criteria about different design features on the hardware that the team needed crew input on to influence the design. Criteria for each evaluation is developed based on several factors. Prior to the evaluation, the project reviews requirements to determine what areas of the design still needed to be further iterated. Results (if available) from previous evaluations play a significant role into whether a specific criterion needs more feedback and should be included on the questionnaire. Previous findings help to identify areas that the crew deemed important and may require further evaluation or consideration as the design matures. These specific areas of interest also help to focus the criteria and any additional questions for the questionnaire so that the team can refine the design further. As well, the fidelity of the prototypes to be evaluated also influence whether a criterion could be adequately assessed during the evaluation and could provide valuable input to the design. Four types of data are collected at each evaluation: criteria rating, criteria importance, criteria rankings, and general comments and questions on the overall design.

Criteria rating asks for a rating of each criterion based on a 1-5 Likert Scale (Completely Unacceptable to Completely Acceptable). Criteria importance focuses on how important the criteria is for overall use and function (Not Important to Very Important). Figure 6 shows an excerpt of a questionnaire that provides an example of a criteria, criteria rating and importance that was used during one of the evaluations.


Rate the design on following criteria:

Completely Unacceptable 1 — 2 — 3 Neutral — 4 — 5 Completely Acceptable

Importance scale: (N)ot Important -> (S)omewhat Important -> (I)mportant -> (V)ery Important

Criteria	Design 1	Notes / Importance of this criteria
Interface:		
Ability to align to body		N S I V

Figure 6. Example of Questionnaire Criteria and Likert Rating Scale including Criteria Importance.

If multiple design solutions or prototypes are being evaluated the test subject is asked to rank the design for that specific criterion from best to worst. Finally, as part of the evaluation, the test subject is asked to provide any additional general comments or feedback that they deem important to the design. For the project, this open candid feedback is the most valuable since it often provides the project insight into how previous space toilets have been used, how the LOO hardware may be used and what improvements or features might improve overall usability for each test subject.

2. Mock Evaluation

After the initial questionnaire flow had been mapped out, the team would perform a mock evaluation with the prototype hardware and stand-in test subjects. Completing a mock evaluation proved to be extremely beneficial in many regards and for the majority of the evaluations several mock evaluations were held prior to the actual one. The mock setup provided a chance for the team to become familiar with the prototypes and learn the details that need to be explained to each test subject. Secondly, the questionnaire is reviewed in detail and the run-through allows the team to also hear how the questionnaire would be presented to each test subject. This allows for iteration on the questionnaire and flow of the information to guarantee two things: 1) that the team is asking the right questions to gain the knowledge they needed for the design and 2) to efficiently conduct each evaluation the same to minimize the impact on the test subjects' schedules. It is important that each evaluation is conducted in a similar method so that each test subject hears the same information and questions and to reduce any potential bias or influence when giving their feedback. Finally, the mock evaluations give the test conductors practice opportunities on how to ask questions and request any additional information during the evaluation if needed.

3. Data Analysis and Summary Memo

Once a series of evaluations have been completed, the team consolidates all the raw data collected for each test subject. It is important that data collected is protected and anonymity is a high priority during these evaluations. For each evaluation, each test subject was given a unique numerical identifier to keep their comments and ratings private and secure.

After the evaluations, the ratings, rankings, and any verbal comments are reviewed and analyzed to determine the overall results of the evaluations. Criteria ratings are averaged and weighted (based on Criteria Importance) across test subjects to determine if the design or specific design feature presented was an acceptable solution. Weightings are calculated so that if one criterion was much more important than another, the multiplying factor could be added on, or taken off in the case that a criteria was less important. This means that the weighted averages consider the sum of the weights of the individual crew members. However, in reviewing the data for each evaluation, the weighted averages did not tend to move very far in any direction, as most test subjects feel strongly about the same aspects of the design. Criteria rankings are tallied to determine the overall best design if multiple solutions were evaluated by the test subjects.

In addition to the numerical data and analysis, the general comments and feedback provided by each test subject are reviewed to identify any additional rationale or data on why a test subject preferred a particular design or feature. The general comments also provide insight into what did and did not work on previous systems as well as how the test subject would typically use the hardware. For each evaluation, a summary of the findings is then documented in a "Crew Evaluation Summary Memo". The memo includes an overview of the hardware evaluated, a summary of the findings based on the data analysis and interpretation, along with the numerical data tables with the preference percentages and average rating data, and a consolidated list of all the general comments. Both the qualitative and quantitative data collected in this memo is used by the project team to influence the next phase of design iteration and the next round of crew evaluations.

V. Crew Evaluation Details and Results

Since the start of the project, the LOO team has completed four crew evaluations. The test subjects that have participated in the evaluations have included crew with and without flight experience on varying vehicles and missions. Additionally, the evaluators have been a mix of both female and male crew which is important since the LOO hardware must provide accommodations for both genders to use the system with their anatomical differences. The details below provide a summary of the prototypes used at each evaluation, the results of the evaluation and how the data was used to influence the next design iteration and evaluation.

A. Crew Evaluation #1

The first series of crew evaluations of LOO prototype hardware was conducted from February 9 -March 11, 2021. The purpose for evaluation #1 was to gather feedback on low-fidelity prototype designs that consisted of two (2) toilet structures, three (3) seats, and four (4) concepts for the Artemis Bag (AB). The prototypes were evaluated for both microgravity and lunar gravity operations. Figure 7 shows the toilet prototypes assessed during Evaluation #1, while Figure 8 shows the Artemis Bag prototypes assessed during the evaluation.

Figure 7. Evaluation #1 Toilet Assembly Low-Fidelity prototypes.

Figure 8. Evaluation #1 Artemis Bag Low-Fidelity prototypes. Four different designs were evaluated.

The test subjects assessed several hardware features of the Toilet Assembly designs. These included structure height, seat-opening size, seat shape/contour, seat comfort, fecal bag placement, fecal bag attachment method, restraint types, and lid features. The test subjects also evaluated Artemis Bag features that consisted of mounting method/interface, restraint types, closure method, and method for initial separation of waste from the body. The test subjects were also asked to provide feedback on the ease of cleanliness for each of the Toilet Assembly and Artemis Bag prototype designs.

A total of 14 test subjects participated in the evaluation. Participants included both females and males as well as flight experienced and inexperienced members. Data analysis determined the preferred features for the Toilet Assembly included: 1) the smallest seat opening size with a saddle shape, 2) placement of fecal bags over the seat, 3) elastic as the method to attach the fecal bags to the seat and to close the fecal bags after use, 4) access to both foot and hand restraints, and 5) an emphasis on ease of cleaning for all parts. Preferred features for the Artemis Bags were determined to be a waist restraint with the ability to attach the bag to the body in different ways, a drawstring as the method of bag closure, and a way to manually wipe or squeeze from outside the bag to achieve initial fecal separation.

B. Crew Evaluation #2

The second round of crew evaluations of LOO prototype hardware was conducted from January 31-February 11, 2022. These evaluations covered the next iterations of lower-fidelity prototypes for the Artemis Bag. Test subjects reviewed three (3) different Artemis Bags concepts with a total of three (3) different styles of bag holder or seat, along with varied restraints and seals, for both microgravity and lunar gravity operations. Figure 9 shows the Artemis Bag prototypes assessed during this evaluation.

The assessed Artemis Bag features included the ability to align, interface comfort, ability to control and keep the hardware secure during operations, use during simultaneous operations, effectiveness for waste separation, ability to enclose waste during removal from the body, and ease of cleanup after use. The Artemis Bag concepts were presented as a set of design features that could be mixed-and-matched to create a final design.

Figure 9. Evaluation #2 Artemis Bag prototypes – three designs evaluated.

A total of 8 test subjects participated in the evaluation. There was a mix of female and male participants as well as flight experienced and inexperienced members. Some test subjects also participated in crew evaluation #1. The data from the previous evaluation was used to develop the three prototypes evaluated in crew evaluation #2 and to generate the evaluation criteria. All three designs included a dual bag concept with a primary bag that holds the deposit and a secondary bag that holds the primary bag and any consumables used to clean up. The secondary bag has a separate seal and could be designed to contain odors. The preferred features from the evaluation data were foot restraints for all designs in microgravity to provide a hands-free option, elastic as the primary bag closure method, folding to secure the secondary bag closed rather than elastic or a drawstring, and incorporating a hand "cot" (similar concept to the finger "cot" on the Apollo Bag[1]) into the primary bag design to allow for pinching or wiping from outside the bag to achieve initial fecal separation. A common piece of feedback was to minimize crevices, seams, porous materials, and other features that would be difficult to clean. The results from this evaluation led to the elimination of some features from the trade space that were rated low by the crew. Two Artemis Bag designs emerged based on the top features rated during the evaluation. Figure 10 shows an excerpt of a design feature summary table.

Features		AB Design #1	AB Design #2	Not Moving Forward
Bag Features	Primary Closure	Elastic	Drawstring	Twist and Secure
	Secondary Closure	Fold and Secure	Peel and Stick	Ziploc

Figure 10. Excerpt of Artemis Bag crew evaluation #2 Design Feature Summary.

C. Crew Evaluation #3

The third series of crew evaluations of LOO prototype hardware was conducted from June 20–July 8, 2022. These evaluations focused on low-to-medium-fidelity prototypes for the second iteration of the primary waste collection system, the Toilet Assembly. Test subjects reviewed one overall assembly structure for both microgravity and lunar gravity operations. The Toilet Assembly prototype included a hinged lid, hinged seat base, seat, fecal bag, Removable Waste Bag (RWB), urine hose cradle, urine hose, urine funnel, and urine bladder. Test subjects also evaluated the need for and placement of foot and other types of restraints. Internal Toilet Assembly components, such as the peristaltic pump and odor filters, were not included in the prototype and are planned for future evaluations. Figure 11 shows the Toilet Assembly prototype hardware assessed during Evaluation #3.

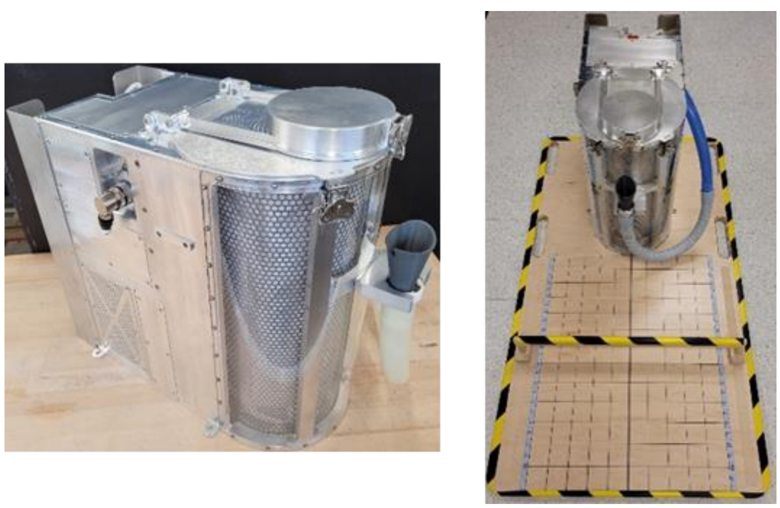


Figure 11. Evaluation #3 Toilet Assembly prototype.

Test subjects were asked to evaluate Toilet Assembly features that included seat indices of back rise and rim width, seat comfort and ease of use, ease of cleanup, fecal bag closure, urine cradle location, urine hose length - for urination only, for simo ops and for menses collection, lid latches, lid swing angle, RWB size and operations, urine bladder size, urine bladder quick-disconnect operations, circuit breaker location, and restraint types and locations.

A total of 10 test subjects participated in the evaluation. Like the previous evaluations there were a mix of female and male participants with various levels of flight experience. Some test subjects also participated in the previous two evaluations. In summary, there were no prevailing negative comments about the components or overall design. There was a general acceptance of the seat shape and placement to allow for simultaneous operations with the urine funnel or BUS. As well, there was a general acceptance of the urine hose length and that simultaneous operations could be achieved with the hose length provided. There was also an overall acceptance of the urine bladder size and QD mechanism to install and remove the bladder from the structure. Finally, the test subjects provided several comments on improving overall cleanliness and reducing crevices on the hardware to make it easier to clean if it is fouled during use. Comments were made on changing the latch design and potentially covering the screw heads on the structure or using another fastener type.

D. Crew Evaluation #4

The fourth and most recent (to date) series of crew evaluations of LOO prototype hardware was conducted on September 15, 2022. The goals of these evaluations were to review updated prototypes for Artemis Bag; introduce the design concepts for the LOO BUS, which is the alternate urine collection system; evaluate the need for menses collection hardware during backup ops; and evaluate simo ops with the two alternative systems. As done during the previous evaluations, test subjects assessed all prototypes for use during microgravity and lunar gravity operations.

Test subjects reviewed two (2) different Artemis Bags, which interfaced with the same redesigned seat that had a new adjustable, wall-mounting option. Feedback on an Artemis Bag secondary/odor bag was also obtained. Evaluators were provided with the concepts for the male and female versions of the Backup Urine System. The female BUS unit was assessed with its female interface and an optional menses collector. Figure 12 shows the Artemis Bag prototypes assessed during evaluation #4, and Figures 13 and 14 show the Backup Urine System prototypes presented during the same evaluation.

Figure 12. Evaluation #4 Artemis Bag - two prototype designs including hand-held and wall mounted seat.

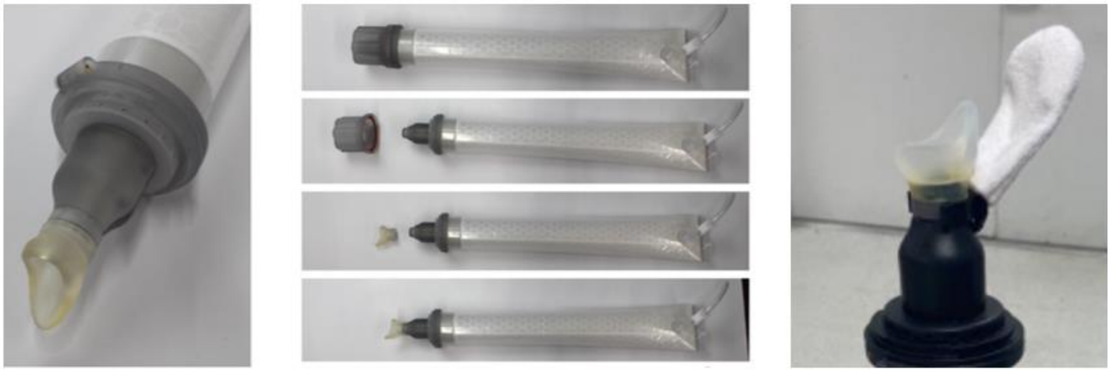


Figure 13. Evaluation #4 Backup Urine System (BUS) prototypes - female interface (left) female interface installed on BUS with cap on/off (middle), and menses collector (right).

Figure 14. Evaluation #4 Backup Urine System (BUS) prototypes with the male interface (left) and BUS male interface with cap on/off (right).

The updated Artemis Bag features were evaluated for both the handheld and wall-mounted seat configurations. Test subjects assessed the ability to attach the Artemis Bag to the seat; bag security when attached to the seat; ability to align the AB to the body; ability to maintain control during operations; anticipated effectiveness of fecal-separation component for initial waste separation; bag removal from seat; bag-closure mechanism; and ease of cleanup. The features evaluated for the secondary/odor bag were anticipated usefulness of added hook-and-loop fasteners for temporary stowage; ability to enclose the Artemis Bag and consumables; and effectiveness of closure mechanisms.

The Backup Urine System (BUS) was based on a crew-approved design for the CCU; therefore, test subjects did not evaluate the design features of the CCU, but instead were asked to provide feedback on the addition of the menses collector and ability to perform simultaneous operations for the BUS.

A total of 6 test subjects participated in the evaluation. As in the previous evals there was a mix of female and male participants with various levels of spaceflight experience and involvement in previous LOO crew evaluations. This was the third evaluation including Artemis Bag prototypes and the variation between the two designs presented was minimal. The crew preferred the primary bag closure mechanism to be elastic drawstring to allow the bag opening to stretch over the seat and remain secured but also allow the crew to close it tightly with the drawstring when removed from the seat. The crew also preferred the built-in wipe with a hand pocket over the hand “cot” feature on the primary bag for initial fecal separation. There was general acceptance of the secondary bag design and hand-held seat that could also be mounted to the wall for hands-free operation of the AB. Some design modifications would be necessary to allow for simultaneous operations with the seat and the urine funnel (on the Toilet Assembly) or BUS. The BUS design baseline was taken from an Orion alternate urine collection system design and was deemed acceptable by all participants for HLS use pending any necessary design changes to meet HLS requirements.

VI. Forward Work

The results of crew evaluation #3 on the Toilet Assembly prototype concluded that the crew found the design of the LOO seat and fecal bag an acceptable solution that should be used on other toilet systems. Overall, the test subjects agreed that the seat design including shape and size were adequate. The seat provides a retention groove to accommodate the over-the-seat fecal bag interface (see Figure 15).

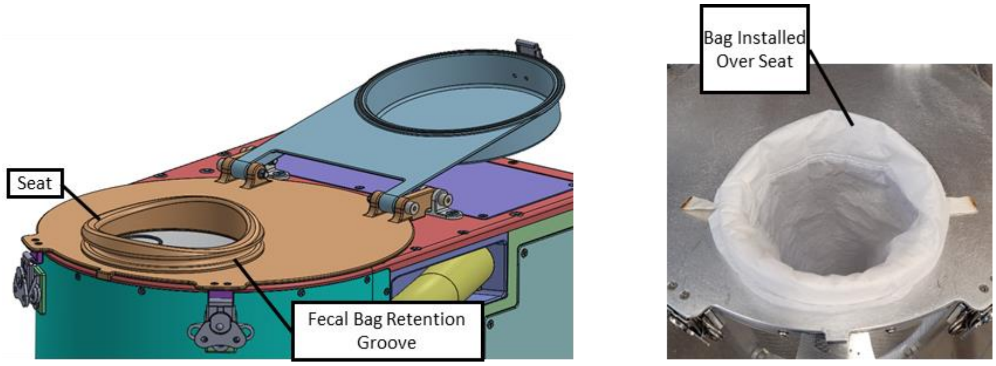


Figure 15. Seat and Fecal Bag Interface (left). Fecal Bag installed over seat on the Toilet Assembly prototype used during crew evaluation #3 (right).

Based on crew comments, this design solution minimizes potential fouling of the seat interface as well as provides an immediate surface for the feces to adhere to once it is separated from the body to potentially minimize escapes from the system. In January 2023, the project team was tasked to develop and certify the LOO designed seat and fecal bag for the ISS UWMS. The objective will be to perform a technology demonstration of the hardware on the existing UWMS to gain crew feedback on usability and overall system performance in a microgravity environment with the new hardware.

Design changes will be required to interface the LOO seat design to the UWMS structure; however, since the current UWMS seat is removable changes should be minimal. Currently the plan is to deliver the hardware in late spring 2023 for a potential launch on SpX-28 with the goal to complete the technology demonstration in late summer. Once the demonstration is complete and hardware operations proven successful then the next step will be to build, deliver and certify the same seat and fecal bag hardware for Orion. The plan would be to replace the hardware on the Orion UWMS unit for Artemis-2.

VII. Conclusion

The crew evaluations for the LOO hardware have been vital to the hardware design that has been completed to date. In total, the project had 38 evaluations completed over the four evaluation periods with many of the test subjects as repeat evaluators. Having repeat evaluators is a vital benefit to the design since this provides continuity throughout the design iteration and the test subjects can see the results of their input and feedback through the design changes that are implemented. The space environment introduces many challenges (such as microgravity) that cannot be fully understood here on Earth. Having testing subjects that are end users of the hardware with and without flight experience is an important component of the design phase of any project since they ultimately will use this hardware in the spacecraft environment. Toilets in particular are not an easy system to design for space flight especially since users have anatomical variations and could use the system differently. Having crew input often and early in the design phase can be a great benefit.

At the end of January 2023, the LOO project was put on hold. The project completed a Preliminary Design Review (PDR) in early January with its HLS stakeholders. If the project is reestablished at a later time, the team will work to finalize the hardware designs through the Critical Design phase and then complete flight hardware build, certification, and delivery. The project will continue to conduct crew evaluations as part of the design process going forward. The crew feedback received during the evaluations has proven invaluable to the design maturity to date and will continue to play a critical role to the design completion.

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References

[1] Broyan, J. L., "Waste Collector System Technology Comparisons for Constellation Applications", 2007-01-3227, 37th International Conference of Environmental Systems, Chicago, Illinois, 2007.

[2] Link, D. E., Broyan, J. L., Philistine, C., and Balistreri, S. F.," International Space Station USOS Waste and Hygiene Compartment Development", 2007-01-3101, 37th International Conference on Environmental Systems, Chicago, Illinois, 2007.

[3] McKinley, M.K, Broyan, J.L, Shaw, L, Borrego, M., Carter, D., Fuller, J., "NASA Universal Waste Management System and Toilet Integration Hardware Delivery and Planned Operation on ISS. 50th International Conference on Environmental Systems, ICES-2021-403, July 7-11, 2021, virtual.

[4] McKinley, M. K., Borrego, M. A., DeRees, K., Williamson, J., Kaufman, C., "NASA Exploration Toilet On-Orbit Results and Impact on Future Missions", ICES-2023-038, 52nd International Conference on Environmental Systems, Calgary Canada, 16-20 July 2023.