

Development of an In-line Urine Monitoring System for the International Space Station

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ABSTRACT

Exposure to microgravity during space flight causes bone loss when calcium and other metabolic by-products are excreted in urine voids. Frequent and accurate measurement of urine void volume and constituents is thus essential in determining crew bone loss and the effectiveness of the countermeasures that are taken to minimize this loss. Earlier space shuttle Urine Monitoring System (UMS) technology was unable to accurately measure urine void volumes due to the cross-contamination that took place between users, as well as to fluid system instabilities. Crew urine voids are currently collected manually in a flexible plastic bag that contains a known tracer quantity. A crew member must completely mix the contents of this bag before withdrawing a representative syringe sample for later ground analysis. The existing bag system accuracy is therefore highly dependent on mixing technique.

The International Space Station (ISS) UMS has been developed as an automated device that collects urine from the Waste and Hygiene Compartment (WHC) urinal funnel interface, separates the urine, measures void volume, and allows for syringe sampling. After the ISS UMS has been used by a crew member, it delivers urine to the WHC for normal processing. The UMS plumbing is then flushed with a small volume of water. The current ISS UMS design incorporates an innovative rotary separator that minimizes foaming, consequently greatly reducing cross-contamination among urine voids (<0.5 mL

urine) while also providing accurate volume measurements (<±2% error for 100 to 1,000 mL void volumes). ISS UMS performance has been validated through extensive ground tests and reduced-gravity aircraft flights. The locker-sized ISS UMS is currently undergoing a design modification that will permit it to interface with the ISS Node 3 WHC Russian toilet (ACY) hardware. The operating principles, characteristics, and results of this design modification are outlined here.

INTRODUCTION

Measuring and assessing urine voids is a critical aspect of the medical monitoring of crew health on orbit. Salvia, blood, and urine are routinely collected on orbit and returned for ground analysis to determine changes in crew member metabolism and health resulting from exposure to microgravity. Collecting urine samples is noninvasive and reduces the need for blood draws. The human body excretes many chemicals and molecules in urine that can be used to monitor musculoskeletal changes (bone loss) and kidney stone formation. Monitoring of both the total urine volume and its chemical constituent concentrations during a mission can aid in the early detection of health issues and help to assess the effectiveness of microgravity countermeasures, e.g., nutrition, prescription medications, and exercise routines. The Urine Monitoring System (UMS) directly measures the total urine void volume and enables

sample syringes to be drawn for subsequent constituent measurement. Urine constituent analyzers can be integrated into the UMS during future upgrades.

Urine and fecal waste is typically collected in microgravity using airflow to entrain them and draw them into a collection device for either disposal or subsequent processing [1]. Current medical collection of urine samples is achieved with Urine Collection Device (UCD), which are bags that incorporate surface catheters that are crew member time-intensive, can result in unhygienic conditions, and have thus received negative crew feedback. The UCD contains a lithium tracer that must be manually mixed with collected urine before a sample, which is manually withdrawn with a syringe, is stored for later ground analysis. The lithium concentration of the sample that is used to determine the original urine volume is susceptible to incomplete manual mixing variations that limit its overall accuracy.

The International Space Station (ISS) UMS is an automated UCD that collects individual crew member micturitions, separates and measures total urine void volume, allows for sampling, and transfers urine to downstream waste collection and processing hardware. The ISS UMS was designed for use in microgravity with either the shuttle Waste Collector System (WCS) or the ISS Waste and Hygiene Compartment (WHC). The ISS UMS consists of a unique rotary separator, fluid management to minimize residual urine, measurement instrumentation, urine syringe sampling provisions, and associated control and display electronics. The ISS UMS does not incorporate a fan to collect the urine but uses the downstream WCS fan to reduce overall hardware mass.

MAJOR UMS REQUIREMENTS

SCIENCE REQUIREMENTS

The UMS science requirements are derived from similar ground-based urine analysis. Urine volume and constituents vary substantially between the first-morning micturition and those that are taken later in the day depending on exertion, fluid intake, and body metabolism. For metabolic analysis, typically all urine voids are collected over a 24-hour period to allow for a composite sample prior to analysis. Collecting and storing each individual's urine throughout the day with a single device is not practical on orbit. Although the Skylab's waste collection system stored individual crew member urine voids throughout the day, it required a dedicated collection system for each crew member [1] which required significant equipment mass. As a result, the single UMS must accurately measure the volume of each crew member's micturition. Individual micturition volumes can range from 30 to 1,000 mL, with an average volume of about 330 mL. The UMS volume accuracy requirement is $\pm 10\%$ for void volumes that are between 30 and up to 100 mL, and $\pm 2\%$ for void volumes that are above 100 mL and up to 1,000 mL.

The volume accuracy requirement is particularly challenging since the specific gravity of urine varies from 1.005 to 1.040. Moreover, if errors from evaporation, viscosity, and ambient pressure are unaccounted, it is not possible to meet the volume accuracy requirement. System considerations to address accuracy will be reviewed in the following measurement approach and accuracy correction sections.

In addition to accurate volume measurements of individual voids, syringe samples from each void are required to analytically create a 24-hour total void sample based on a volume-weighted average of all the samples. Therefore, the ISS UMS must allow for crew member-drawn samples of urine void volume. The ISS UMS uses existing urine sample syringes of 7.5 and 10 mL that were also used by the previous shuttle UMS and the current UCD kit. The ISS UMS allows one syringe for 30- to 50-mL voids, two syringes for 50- to 100-mL voids, three syringes for 100- to 500-mL voids, and four syringes for 500- to 1,000-mL voids.

The ISS UMS must avoid cross-contamination between crew members to achieve its science requirements. As the next micturition will most likely be from a different crew member, cross-contamination among crew members must be avoided. This is particularly important if the following void volume is on the low side of the volume range. This is because cross-contamination changes the constituent concentrations of the following void volume. The UMS cross-contamination requirement is ≤ 0.7 mL of urine transfer among subsequent crew member micturitions.

Additionally, if the unit is cleaned with fluid between crew member micturitions, the residual fluid volume must be kept low to avoid diluting the following micturition volume and its constituent concentrations. The ISS UMS fluid residual requirement is ≤ 5.0 mL among subsequent crew member micturitions.

Cross-contamination and liquid residual requirements require many small design features and operational considerations to meet these requirements. A few of these will be reviewed in the following fluid management and cross-contamination sections.

HARDWARE/OPERATION REQUIREMENTS

The ISS UMS hardware must be capable of being launched within a shuttle mid-deck locker. This limited the overall size of the UMS to approximately 44 by 23 by 23 cm. Additionally, the ISS UMS must be compatible with existing U.S. urinal funnels and urine pretreat chemicals. As the UMS connects upstream of the nominal WCS/WHC, its pressure drop must be minimized to prevent an adverse reduction in airflow rate. The UMS air pressure drop is limited to ≤ 3.4 kilopascals at 340 L/min. This pressure drop limits the number of features that are available for separating the air and the urine. The UMS must also maintain an acoustic emission that is less than

62 dBA, which impacts the motor and bearing designs of the rotary separator.

To reduce crew member time, the hardware automatically associates a crew member with a urine void volume and sample syringe number. The crew member must be able to withdraw syringe samples with one hand in microgravity. The sample port must also be able to accommodate the length of both the existing 7.5-mL preservative syringe and the 10-mL frozen syringe.

HARDWARE DEVELOPMENT

There have been two different technical approaches for UMS: the initial shuttle UMS and the ISS UMS. The latter is the focus of this paper, but a brief review of the shuttle UMS provides a basis for the current ISS UMS approach.

The current ISS UMS design is to replace the original shuttle UMS that was developed in the 1980s. The shuttle UMS experienced substantial liquid loss in the airstream and liquid cross-contamination among subsequent users. Both issues contributed to a loss of scientific accuracy. Multiple design modifications that occurred over seven shuttle flights to improve the accuracy could not resolve the inherent performance deficiencies of the unit. The shuttle UMS design incorporated a rotary separator with a stationary bowl and a series of rotating paddles and screens to accelerate and rotate the fluid. Fluid pressure was measured through a pitot tube using the stagnation pressure that was created by fluid rotation. Fluid was also drained through the pitot tube. These design features created excessive turbulence, foaming, and "dead-flow" areas that could not be resolved despite multiple redesigns.

The current ISS UMS design began in 1999 with a rotary separator that employed a distinctly different technology approach [2, 3]. The ISS UMS separator uses a bowl and paddles that rotate at the same speed. This produces near-solid body rotation of the fluid through most of the bowl volume, and greatly reduces the turbulence and foaming within the unit; this will be detailed later in the fluid management section.

The ISS UMS was devised as a two-stage flight project. Although the design was to meet all of the ISS requirements, the initial flight article was to fly as a detailed test objective (DTO) on the shuttle and interface with the shuttle WCS. The DTO unit was to have identical fluid performance to the ISS UMS flight unit to allow on-orbit verification of accuracy and cross-contamination. The separator bowl and portions of the mechanical enclosure were also constructed out of transparent materials to confirm that the microgravity fluid performance matched the analytical predictions.

The ISS UMS DTO flight unit was fully assembled; its key components were tested on NASA reduced-gravity

aircraft to validate microgravity performance. However, due to program constraints, the shuttle DTO flight was removed from the schedule and the DTO ISS UMS is now being converted to the permanent ISS UMS configuration. The ISS UMS was designed to be fully compatible and to interface with the U.S. ISS WCS. Due to ISS Program constraints, however, it was replaced with an adaptation of the Russian Service Module toilet (ACY) [4]. The Russian ACY uses airflow to entrain urine in a manner similar to that of the U.S. ISS WCS and U.S. shuttle WCS. This paper uses the DTO ISS UMS to describe the common features of both units. Unique features to the ISS UMS configuration and modifications that are required for Russian ACY compatibility are described at the end of paper.

The DTO ISS UMS consists of two major subsystems: the avionics module (AM) and the mechanical module (MM), as shown in Figure 1. The AM, which contains the crew interface, display, and processing electronics, is about 25 x 23 x 14 cm and weighs approximately 4 kg. As the AM is one of the components that is being replaced in the current design modifications, it is not discussed in detail below. The MM contains fluid handling hardware, instrumentation, and power conversion and hardware control electronics. It is approximately 44 x 23 x 23 cm and weighs about 23 kg. In addition to the AM and MM, the ISS UMS also consists of ancillary support hardware including external fluid hoses, electrical cables, a sample syringe kit, and a validation syringe kit.

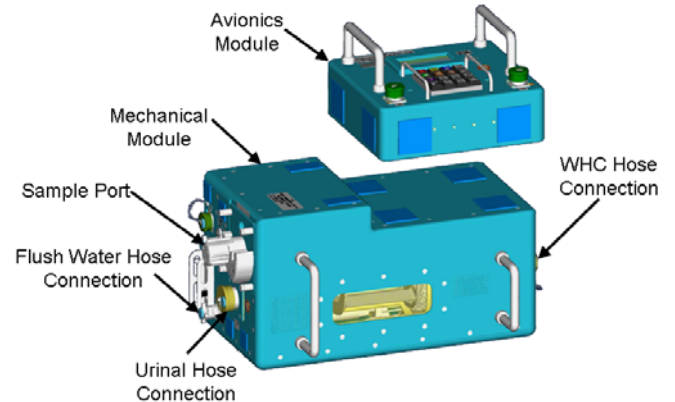


Figure 1. The DTO ISS UMS AM and MM hardware.

The DTO ISS UMS would have attached to the vehicle WCS urinal hose connection (see Figure 2). This connection allows either the vehicle WCS fan to draw approximately 340 L/min through the unit. The airflow entrains the crew member urine stream as a two-phase flow (urine/air mixture) into the DTO ISS UMS urinal funnel and hose. This mixed flow immediately passes through a mesh screen prefilter to remove large debris that could reduce the life of the separator. The mixed flow then enters the rotary separator, where the urine is directed toward rotating surfaces and centrifugal force drives this urine to the bowl outer wall where the entire void volume collects in an annular ring of fluid. Air

passes through the center of the separator, through solenoid valve 3 (SOL3 in Figure 2) which is open, and exits back to the WCS.

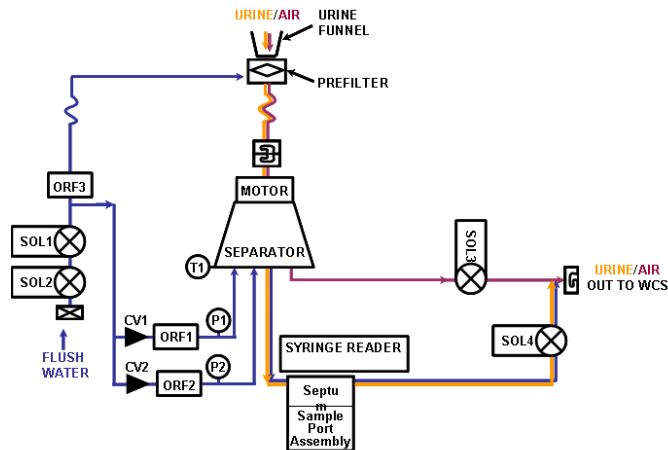


Figure 2. ISS UMS flow schematic illustrating major components and flow of air, urine, and flush water.

The urine that is collected in the separator bowl has multiple pressure measurements taken to determine its volume. Solenoid valve 4 (SOL4 in Figure 2) is opened briefly to charge the liquid outlet line to the sample port assembly. The crew member can then draw syringe samples as directed by the AM. After sample collection is completed, Solenoid valve 4 is opened again to drain the residual urine from the separator. The drained urine is recombined with the airflow before it is delivered to the WCS. This system enables the WCS to receive the same two-phase urine/airflow and to operate the in the same manner (except for total cycle time), whether the ISS UMS is present or not. The crew member interface is essentially the same for both the ISS UMS and the WCS.

The ISS UMS also has a connection to the vehicle water supply that is used to flush out residual urine contamination. Water flow is provided by vehicle water supply pressure through two redundant shutoff solenoid valves and orifices that distribute the flow among three parallel paths. The primary path for 95% of the water flow is through orifice 3, which provides flush water below the urinal funnel. This enables flushing of the urinal hose and separator bowl. The remaining 5% of flush water passes through pressure-sensing lines to the separator bowl. This minimal water flow is sufficient to counteract any intrusion or diffusion of urine into the small pressure-sensing lines. This flushing prevents precipitation buildup that could occur over time. The flush water is then drained through solenoid 4 to the WCS. At this time the ISS UMS enters a standby mode until the next crew member usage.

MEASUREMENT APPROACH

The ISS UMS measurement approach is theoretically straightforward. The rotating separator bowl creates essentially solid-body rotation in an annulus of fluid, as shown in Figure 3.

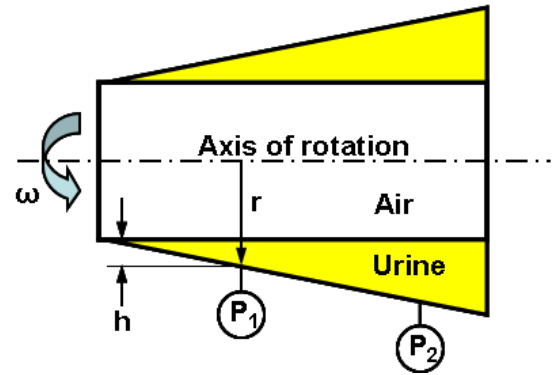


Figure 3. Idealized cross section of a rotating separator illustrating fluid accumulation and pressure sensing locations.

The theory of the rotating separating bowl can be simplified into a few basic equations that follow. Note, that edge effects details do impact the fluid pressure but are not considered here. For the above figure and following equations the following terms are defined: pressure (P) increases with submerged depth (h) and centrifugal acceleration (g) due to rotation and distance from the rotational axis:

$$P = \rho * g * h$$

$$\text{where, } g = \omega^2 * r$$

$$\text{substituting returns, } P = \rho * \omega^2 * r * h.$$

In actual usage, the density (ρ) of the fluid is unknown; but if pressure is measured at a known radial location (r), the depth of fluid can be calculated. Since the separator bowl cross-section is known at each depth, and assuming an average density, the pressure can be empirically calibrated to the liquid volume in the separator bowl. However, the density of urine varies from 1.005 to 1.040; so if it is left uncorrected, the ISS UMS could not meet its accuracy requirement of $\pm 2\%$. If a second pressure transducer is added to a different radial location, the density can be calculated.

$$P_1 - P_2 = \omega^2(h_1 - h_2) * \rho$$

Solving for density allows density to be calculated from rotational speed and pressure measurements, assuming that the location of the pressure ports are known.

$$\rho = C_1 * (P_1 - P_2) / \omega^2(h_1 - h_2)$$

In practice, however, fluids of known density are used to create a calibration curve (C_1) that relates density to the pressure difference between the two transducers. The measured density can then be used to calculate the true volume using the following relationship: