# How Do Astronauts Urinate? The History of Innovations Enabling Voiding in the Void

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Urination in microgravity is a challenge that bedevils all space travelers and intrigues all space watchers. The absence of gravity defies one's terrestrial voiding behaviors. Scientists, engineers, and astronauts refined the interface between man and machine, solving problems, and improving astronaut comfort. From forgotten to familiar technology, the nearly 60-year history of manned spaceflight serves as a testament to the innovation and fortitude necessary to boldly "go" where no man has gone before.

## PHYSIOLOGY OF URINATION IN SPACE

Initially effects of weightlessness on basic physiological functions were unknown. "Highly motivated volunteers" with full bladders boarded roller-coaster zero-gravity parabolic flights and demonstrated that the bladder could be emptied voluntarily.[1] However, voiding is fundamentally different in space.

In microgravity, urine does not collect at the bladder neck. Surface tension becomes the dominant force, and urine adheres to the walls of the bladder. Detrusor distension triggers the urge to urinate only when the bladder is completely full. This impaired sensorium is further compounded by voluntary voiding delays due to schedule or waste control availability, anticholinergic effects from antiemetics for space motion sickness, and possible unmasking of subclinical voiding dysfunction.[2,3] Despite timed voiding, 9 episodes of urinary retention—4 episodes requiring catheterization—have been documented. Retention usually occurs within the first 48 hours of the flight. Females are 4 times more likely to develop retention than male astronauts.[4] Unrelieved urinary retention can be life and mission threatening. Urosepsis has been deemed the third most likely reason for emergent medical evacuation; this risk prompted astronaut education on self-catheterization.[4,5]

## HOUSTON WE HAVE A PROBLEM: INITIAL LESSONS IN THE VOID

Initially all space related innovation was challenging. Space travel was considered fictional and an unfavorable allocation of funding in the 1950s. The National Advisory Committee on Aeronautics, Air Force, Army, and Navy had a vested interest in safer aviation but little collaboration. These forces were not unified until National Aeronautics and Space Administration (NASA) was created in 1958. Furthermore, implicit social conservativism dominated American culture; waste management systems were taboo.[6]

On May 5, 1961, Alan Shepard manned the Mercury-Redstone 3 mission. His flight was planned for only 15 minutes, but he was suited up for over 8 hours due to flight delays. Ultimately, he ended up having to urinate in his space suit. He avoided electrocuting himself but instead shorted out his electronic biosensors temporarily.[6,7] Urination was nearly forgotten. A container for liquid waste was located near the entrance hatch but was inaccessible to a restrained astronaut.[6]

For the Mercury-Redstone 4 mission on July 24, 1961, Gus Grissom wore 2 layers of rubber pants to contain his urine, hopefully avoiding the risk of electrical complications. His morning coffee, a diuretic, was withheld, possibly so that he would not need to try out the new strategy during his short duration flight.[6]

## ALL SUITED UP: WEARABLE URINE COLLECTION DEVICES AND SPACE DIAPERS

Learning from Shepard's and Grissom's historic missions, the need for more efficient waste collection systems was clear. Catheterization was quickly eliminated as an

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option; continued wear was uncomfortable, and infection could be catastrophic.[6,8] Engineers favored existing external catheter designs attached to a storage bag worn around the waist, called Urine Collection Devices (UCDs). After the commercially available condom with least leakage was determined, the latex was swapped for a more durable material and 1 end of the "roll-on-cuff" stretched around the opening in a storage bag. These designs were tested aboard the 0-g parabolic flights.[6] John Glenn was the first astronaut in a long series to wear a UCD during the Mercury-Atlas 6 mission on February 20, 1962. Just before reentry, his UCD contained his 800 mL of urine.[6,9] Similar technology persisted for all astronauts wearing a pressure suit during launch, landing, and during spacewalks until the Apollo missions of the late 1960's.[6,10]

Designs were refined to achieve a pressure differential necessary to pull urine away from the skin and into a storage container. Pressure inside the suit was increased to direct the urine in to the storage bag.[6] When used, the warmth of the urine spread across the abdomen and was associated with worry that the bag had burst. For longer flights, Urine Collection and Transfer Assemblies, comprised of UCD-like roll on cuffs with quick-connect tubing that directed urine from in-suit bags into cabin reservoirs (Fig. 1A). Negative pressure systems were created for UCTSs using a syringe-based design for Mercury-Atlas 9. Crews operating outside of their pressurized suits used a urinal with an extendable bellows assembly for the Gemini 3 and 4 missions. Unfortunately, this system was easily overwhelmed, prone to leakage, and required excessive force or a partner to synchronize negative pressure generation with voiding rate. For later Gemini missions, the bellows were traded for a 1-way valve with greater ease of use.[11] Devices were moderately successful in containing urine but were difficult to position accurately and clean.

Despite equal qualifications, female astronauts could not use a condom-style in-suit UCD or Urine Collection and Transfer Assemblie, and this is postulated by some to have contributed to their delay in joining the astronaut ranks until 1983.[7,12] Female specific prototypes included custom perineal masks covering the entire urogenital area.[13] Other designs contained a smaller cup-shaped device positioned and held adjacent to the urethral opening by an invasive vaginal locator. These cup-shaped designs also were uncomfortable, leaked, and failed to adequately seal the introitus from contact with urine increasing infection risk.[14,15]

In the quest for gender-neutral urine collection methods, NASA turned to existing commercially available incontinence products. Disposable Absorption Containment Trunks, commonly known as space diapers, were first used in 1983 (Fig. 1B). Disposable Absorption Containment Trunks were replaced in 1988 by Maximum Absorbency Garments with additional moisture wicking capability, like high absorbency bike shorts designed to hold up to 2 liters of liquid.[16] Maximum Absorbency Garments are worn during launch, reentry, spacewalks, and emergencies for both female and male astronauts.[13,17]

## VOIDING VIA SPACE VACUUM

Space flight experience by the late 1960's heralded a transition from exploration to experimentation. Previous urine management systems relied upon intimate contact with all male crews. Longer duration missions, high demand for improvement, and the addition of female astronauts drove design improvements.[7] The Soviets were the first to use a vacuum waste management system aboard the Vostok-2 mission in 1961. Cosmonaut Gherman Titov voided into a funnel, and fan-driven partial suction directed the urine to a portable storage container. The funnel shape was modified for use by female cosmonaut Valentina Tereshkova during her 3-day flight (June 16-19, 1963) on the Vostok-6 mission (Fig. 2B). A similar system is used aboard the Soviet Salyut space station, Russian Soyuz spacecrafts and International Space Station.[18-20]

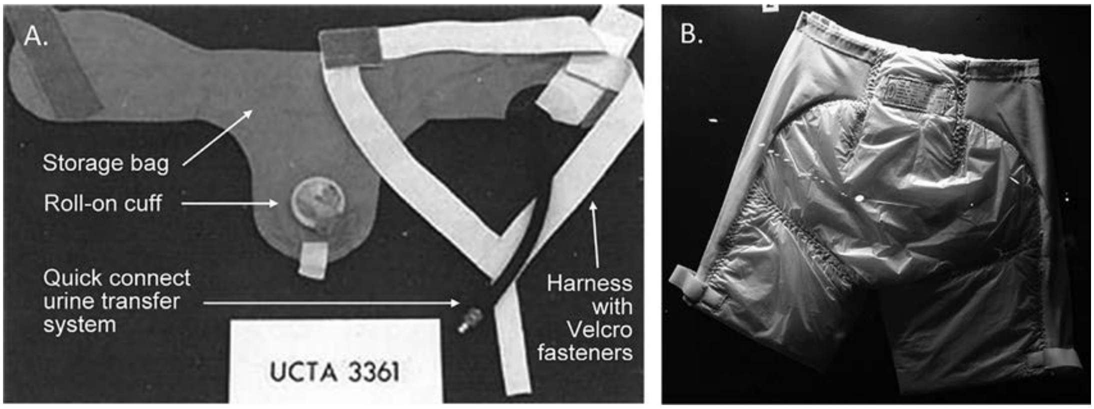


**Figure 1.** Technology enabling in suit urine collection. (A) Urine Collection and Transfer System (UCTA) consists of Urine Collection Device (UCD; roll-on cuff, storage bag) and quick connect tubing to empty urine (NASA photo archive). (B) In suit UCDs or UCTAs were replaced with Maximum Absorbency Garments (MAGs) in 1983 then DACTs in 1988. Disposable Absorption and Containment Trunk (DACT) developed for use by female astronauts on early Shuttle flights on display at Johnson Space Center (photo by Per-Olof Forsberg on Flicker).

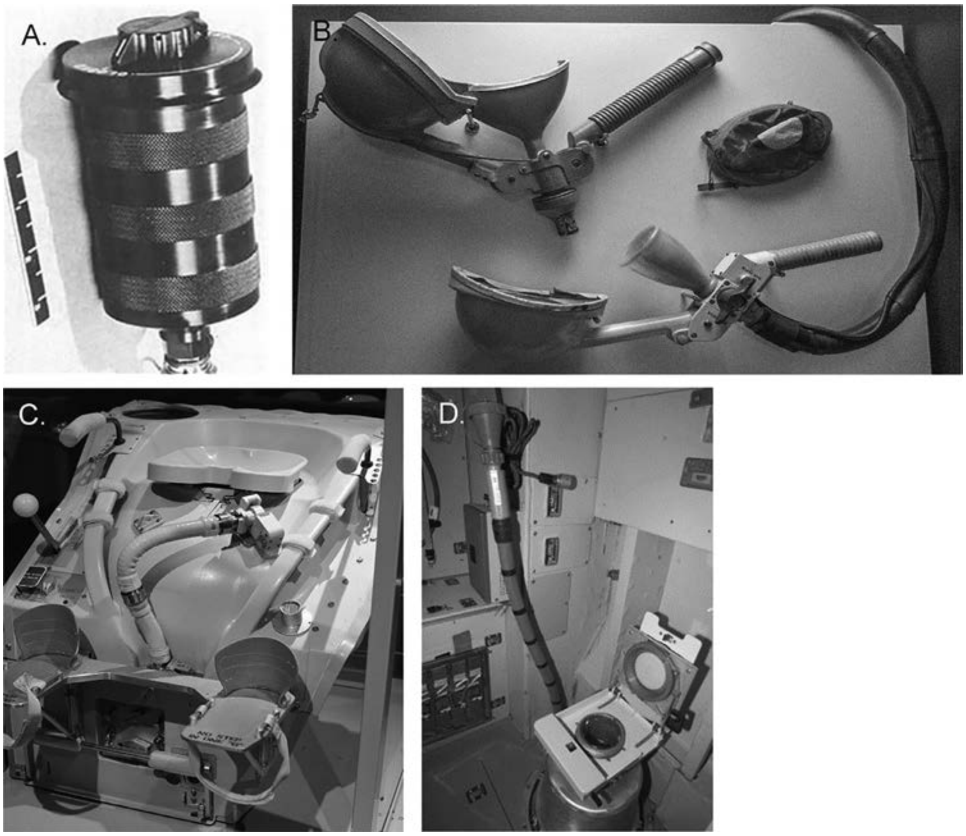


**Figure 2.** Technology enabling urine collection outside of the pressure suit. (A) Male vacuum urinal used during Apollo 12 mission in 1969[9]. (B) Female vacuum urinal first used by Soviet cosmonaut in 1962[17]. (C) Toilet trainer modeled to be the space shuttle vacuum toilet for astronaut practice prior to space flight on display at the Museum of Flight (photo by Adam Foster on Flicker). (D) Vacuum toilet and urinal with Russian design elements aboard the International Space Station in the Zvezda module (NASA photo library). Additional vacuum toilet in the Destiny laboratory.

The 1969 Apollo 12 mission introduced the urine receptacle assembly (URA, Fig. 2A). The astronauts voided into a hand-held, cylindrical container. Urine was held in the container via capillary action. The user's urine stream was collected with air flow created via pressure differential from the cabin to space. Air flow rate was too low for female use. Even for male crew members, a balance between sufficient air flow to collect urine and minimizing loss of cabin oxygen during use was challenging.[10,19] All subsequent US and Soviet or Russian waste collection systems have used air entrainment as the primary waste collection mechanism.[19]

Plans for long-term orbiting facilities in the early 1970s sparked the desire for more durable, hygienic, and gender-neutral waste collection methods: creature comforts favored familiarity over practicality. A balance between microgravity and terrestrial etiquette manifested as a zero-gravity toilet. Air flow pulled waste from its source, directed it to a reservoir and prevented dissemination throughout the shuttle, serving as an alternate flushing method. The air was then filtered and recycled back into the cabin.[21,22] The Skylab space station toilet combined the Apollo URA with hose mounted vacuum funnel adjacent to seat and reservoir for fecal collection. Air flow was increased from the Apollo URA designs to eliminate intimate crew contact and issues with urine splashing.[21] The Soviet/Russian MIR space station and International Space Station (ISS) Russian service module Assenizatsionno Sanitarnaya Ustanovka has comparable technology but cosmonauts share funnels and clean between uses.[19] Designs for the space shuttles improved upon this concept by providing each crew member with their own collection funnel as well as collecting urine and feces in the same reservoir and separating by density via centrifuge.[19] Designs have also improved to accommodate the psychological and vestibular needs of the crews.[7]

Vacuum toilets aboard space shuttles and the ISS bear closer resemblance to terrestrial toilets (Fig. 2C). However, you'll find them bolted to the wall, and deliberate practice is required for successful use. The transport tube has a narrow diameter (4-inches) to achieve sufficient airflow, making aim crucial. Improper positioning can result in feces plugging up air holes around the rim and require the user to complete the arduous task of cleaning them out.[7] The toilet trainer, or "potty cam," is an illuminated closed-circuit camera in a toilet bowl with a monitor. Astronaut Mike Mullane noted that the toilet trainer was the "most memorable" NASA simulator and "took a lot of glamour out of being an astronaut." Memorized position in relation to clamps and seat landmarks is duplicated on the space mission.[8]

Despite the rigorous testing and training, the space toilets have malfunctioned. The first space shuttle toilet aboard the STS-1 in 1981 had a clogged filter prohibiting suction and waste separation by the end of the 2-day mission. Vacuum dried fecal matter was spread throughout the cavity upon reentry.[23] Suction issues were fixed for future missions, but the space toilets require significant maintenance including daily cleaning and replacing filters. On the STS-41D mission in 1984, vented urine froze into a large icicle on the Discovery shuttle's waste dispersion nozzle. The icicle was removed using the shuttle's robotic arm to prevent damage upon reentry as was suspected on a previous mission. In both cases, the crew was forced to return to "Apollo bags".[23]

## NO LONGER REJECT, BUT RECYCLE URINE: A NEW ENVIRONMENTAL PARADIGM

Multiple astronaut memoirs have commented upon the ineffable beauty of the sun-illuminated flurry of sublimated waste-water droplets.[7,8] However, on the ISS water is a highly limited resource. A highly-complex urine processor distills, filters, oxidizes, and iodinates urine to transform it into drinking water.[24-27] Current models are capable of recycling 93 percent of waste water.[22,25] This toilet-to-tap system defies cultural norms. Even the United States and Russia stand divided over water recycling. Both countries recycle condensation. American astronauts drink recycled urine; Russian cosmonauts defer drinking their urine and instead barter their urine with the Americans in exchange for solar energy.[24,28] But toilet-to-tap is not that farfetched; similar technology has helped offset fresh water shortages in Orange County, California.[7]

Space mission success depends upon high-efficiency resource conservation and recycling. It would be impossible to bring enough drinking water for long-term space missions. Without recycling, water could make up to 90 percent of the mass on a space trip to Mars, and an estimated cost of up to $10,000 per pound launched into orbit make it a prohibitively expensive resource.[25] These regenerative capabilities allowed an increase from 3 to 6 crew members on May 29, 2009, aboard the ISS.[29] Even urea is converted to ammonia in a bioreactor to generate electricity.[25]

## CONCLUSION

Space exploration is a study of what it means to be human. Waste collection is an unglamorous but essential part of any space life support system. Initially not emphasized, the urine management systems of today are a far cry from their rudimentary origins on the first manned space flights of the 1960s. The ergonomics, efficiency, and recycling capabilities continue to evolve and incorporate new technological advancements to overcome the absence of gravity. As we push the limits of space exploration, new challenges force one to unlace certain notions of what is and what is not possible.

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## EDITORIAL COMMENT

The authors have provided an informative and entertaining summary of the challenges of micturition in microgravity. They have thoroughly captured many of the technologic evolutions for managing the most basic of human functions-elimination. Employing space vacuum seemed an easy approach to the problem, but was offset for the potential for vehicle decompression, through valve failure, as which induced ebullism and killed the crew of Soyuz 11-Georgi Dobrovolski, Vladislav Volkov, and Viktor Patsayev on June 30, 1971.

Voiding dynamics, access to collection means and the collection process itself have all been barriers to an activity we take for granted in 1-g, on planet Earth. The engineering for waste management without gravity has proven to be somewhat complex, especially when there is a desire to preserve a highly needed and heavy to launch consumable, water. The Soviet Union preceded the United States in space toilet design and implementation. The USSR's first orbital toilets were custom-made, such that cosmonauts G. Titov, A. Nikolayev, P. Popovich, V. Bykovsky, and A. Leonov had their buttocks measured for their personal toilets. A research institute in Moscow still has the bronze toilet bowl, used by the first woman in space, V. Tereshkova.

Zvezda, built the 35 lb potty for the Soyuz and Mir space station, noted for its clever and reliable simplicity, but lack of personalizable interface, and unpleasant emptying. Cleaning the ACY (Assenizatsionno Sanitarnaya Ustanovka, aka Russian space toilet) typically ranks up with the astronauts' and cosmonauts' least favorite mission tasks. As mentioned in the manuscript, urine collection devices and bags were used for many missions, including the last Mercury flight in 1963, when Gordon Cooper wore a UCD that attached to his space suit. Cooper's mission had many failures, several of which required him to manually pilot the spacecraft for reentry. He returned safely, but even a small error could have resulted in disaster. Investigative teams, later determined that Gordon's urine bag leaked and disabled several automated electronic guidance and control systems. During Apollo, each fecal collection bag came with a "finger cot" to allow the astronauts to manually move things along-thereby separating man from his product. Then, after capture, the Apollo crew had to squeeze a germicide into their excrement, so that gas-producing bacteria would not multiply inside the sealed bag and cause it to explode!

Shuttle waste management systems were initially fraught with unpleasant failures, as early as STS-3, requiring multiple system redesigns, which were precipitated by the infamous and odiferousIn-Flight Maintenance of a previously utilized Waste Collection System onboard orbiter Atlantis, during STS-46, by the first Swiss ESA astronaut, Claude Nicollier. There was also a space toilet scandal on ISS in 2007 when, after several failed attempts of their own, NASA bought a Russian toilet for $19 million to install in the US segment, but would not let Russian crew members use it. In 2018, that very toilet broke and US crew members had to borrow the Russian segment toilet while asking RSS Energia for repair parts.

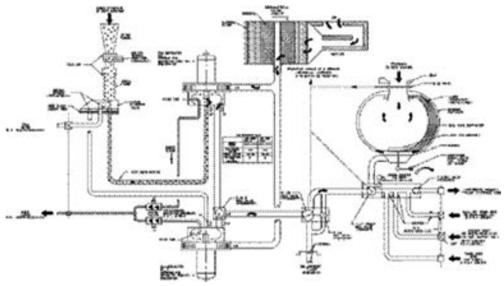
Although, the device worn in NASA's Launch and Entry and Extravehicular Activity space suits-the Maximal Absorbency Garments, aka "space diapers" were made famous for a "discommoding" reason, this technology reduced the morbidity of many with earthbound incontinence; just as much of spaceflight technology has improved the lives of terrestrial people worldwide. The chemical powder absorbent, sodium polyacrylate (SPA) is embedded into the fabric of the undergarment. SPA can absorb approximately 300 times its weight in fluid, (~2L), so the crew can go 10-12 hours without changing, and the water-SPA gel created by use, wicks liquid away from the skin, preventing irritation. The hope will also be that improvements in recycling technology, being employed on the International Space Station and Orion vehicle, as in the Universal Waste Management System, will not only enable human exploration class missions to destinations such as Mars, but also possibly help conserve a precious resource on our planet-potable water.

We cannot leave the topic of space-related urination without mentioning a famous Russian tradition of stopping the crew transfer bus headed to the Soyuz launch facility at the Baikonur Cosmodrome, and voiding onto the starboard, after tire. This tradition began with the first human into space, Yuri Gagarin, who needed to relieve himself before the first spaceflight and did not want to have to go into his spacesuit, like Alan Shepherd had to do a month later, May 5, 1961 on Friendship 7. Thus, Gagarin took liberties in wetting the bus' right, rear tire on April 12, 1961, shortly before he launched into space. There is no indication he intended to start a tradition, and likely was done out of pure necessity; but since he is a national hero of the motherland, other cosmonauts have perpetually emulated him exactly, many out of superstition. And now 50 years later, they are still boldly "going". In case you were wondering, female crew members, are not obligated to participate, due to anatomic considerations, however they often bring a collection cup full of their urine and ceremoniously dump it onto the tire instead!

Photos if there is space or desire by the editors to use them, complementary to the photos selected by the authors.

ISS-Service Module "Zvezda" Toilet-ACY.

ACY-schematic.



Shuttle toilet trainer.

Honoring Yuri Gagarin tradition before Soyuz launch.

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## AUTHOR REPLY

We sincerely appreciate the thoughtful comment accompanying our manuscript. We wholeheartedly agree that physiological changes in microgravity require sophisticated technology, despite the seeming simplicity of voiding.

As highlighted in the commentary, the discoveries that help astronauts eat, drink, and "pee merry" have had direct translations for the earth-bound. Innovations in water recycling and high absorbency space diapers have been translated into applications on earth.

The greatest success of the space program is not only the technological advancements but also the human collaboration. The Space Race started as a competition between the Soviet Union and the United States to secure national security and gain global influence. Even the engineering for waste management echoed the tone of the Space Race; advancements in waste management in space were notable for firsts from both the Soviets and Americans. However, the change in political climate after the fall of the Soviet Union sparked increased areas of cooperation, including strategic partnerships in space. For example, Russian cosmonauts barter their urine with the American astronauts in exchange for solar energy. Today, the International Space Station represents strong "pee-ceful," international collaboration, transcending political barriers.

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