Waste Management Systems for Crewed Spacecraft

A Technical Review and Requirements for Future Habitats

From Apollo to the Universal Waste Management System, with failure modes, water and solid waste recovery, and requirements for commercial stations, lunar surface habitats and Mars transit.

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CONTACT
a@stellaramenities.space

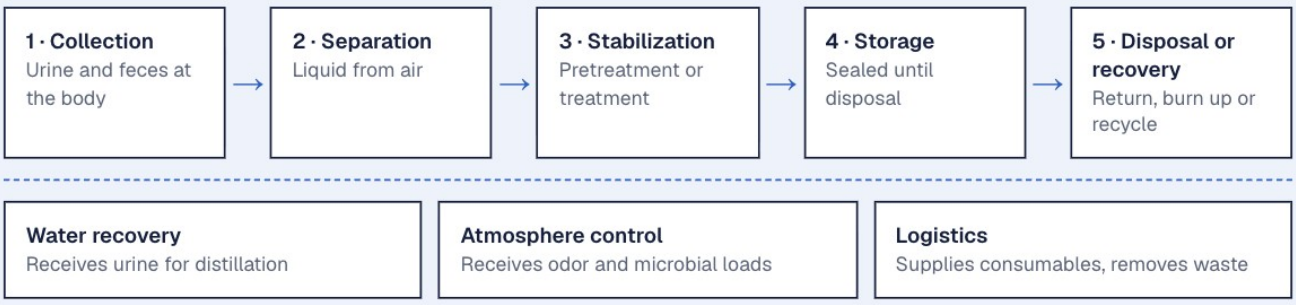
SUMMARY

This review is based on personal communications with two practitioners who have designed crewed spacecraft and their life support systems: an interview with Anthony Sims, former Principal of Industrial Design at SpaceX, and conversations with Grant Anderson, cofounder of Paragon Space Development. Their accounts frame a technical analysis of waste management systems, which have been an engineering challenge in every era of human spaceflight, from the Space Shuttle to the International Space Station and Orion on Artemis II. The review traces the evolution of these systems from Apollo to the Universal Waste Management System (UWMS), analyzes the failure modes that recur across programs with support from NASA technical literature and public mission records, and sets out requirements for waste systems on commercial space stations, lunar surface habitats and Mars transit vehicles.

01 Scope and functions

A spacecraft waste management system performs five functions in sequence: collection of urine and feces at the body, separation of liquid from air, stabilization or treatment, storage, and disposal or recovery. In microgravity each function depends on engineered airflow, because gravity provides separation on Earth at no cost in mass, power or crew time. The system also connects to three other subsystems: water recovery, which receives urine for distillation; atmosphere control, which receives odor and microbial loads; and logistics, which supplies consumables and removes waste. A failure in any one function therefore affects habitability, water balance and crew schedule at once.

EXHIBIT 1 · THE FIVE FUNCTIONS OF A WASTE MANAGEMENT SYSTEM AND ITS INTERFACES



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02 Apollo and Skylab

Apollo crews collected feces in plastic bags with an adhesive rim, mixed a germicide into each bag by hand, and stored the sealed bags for return. Urine passed through a cuff and hose and was vented overboard. The method required no powered hardware, and crews reported it as unpleasant and time consuming. During Apollo 10 in May 1969, solid waste escaped containment and floated in the cabin.

Skylab introduced the first toilet to use airflow for collection in 1973. The system collected feces in bags, dried them under vacuum, and returned samples to Earth for metabolic research, and it also measured and sampled urine for that research. Skylab established the principle that every later toilet adopted, in which fans and airflow replace gravity at the interface between body and fixture.

03 Space Shuttle and the International Space Station

The Shuttle Waste Collection System combined a fan driven urine funnel with a commode that used airflow to direct feces into a storage canister. The system malfunctioned regularly across the program, with fan, separator and blockage faults that forced crews onto contingency bags.

On the International Space Station, the Russian segment uses the ACY toilet in the Zvezda module, and the US segment uses the Waste and Hygiene Compartment (WHC), which integrates a Russian ACY unit with US plumbing that routes urine to the Urine Processor Assembly. In 2008 the Zvezda toilet lost its urine fan, and engineers flew a spare gas liquid separator pump to orbit on a Shuttle mission. NASA paid $19 million for a second Russian toilet so that a six person crew would have two working units. In 2009 the Destiny toilet flooded while thirteen people were aboard the station and a docked Shuttle, and in 2010 calcium deposits clogged the liquid waste processing line.

In late May 2024 a pump in the station's Urine Processor Assembly failed ahead of its planned replacement, and the crew stored urine in containers until a spare arrived. NASA removed two crew suitcases from Boeing's Starliner to fit the replacement pump, roughly 70 kilograms, which flew on the Crew Flight Test on 5 June 2024.

04 The Universal Waste Management System

NASA contracted Collins Aerospace to develop UWMS as a common core toilet for the station and for exploration vehicles, with a goal of reduced mass and volume and improved usability for female crew members. The station unit, delivered in 2020 at a reported cost of $23 million, offers a volume reduction of 65 percent and a mass reduction of 40 percent relative to the WHC toilet. The Orion unit offers a volume reduction of 61 percent relative to the Shuttle toilet.

EXHIBIT 2 · UWMS STATION UNIT COMPARED WITH THE WHC TOILET

65%	40%	$23M
Volume reduction vs WHC	Mass reduction vs WHC	Reported station unit cost

The design uses a 3D printed titanium dual fan separator to provide airflow for collection, and titanium resists the strong acid pretreatment that stabilizes urine before distillation. Airflow begins when the lid opens, which improves odor control, and the funnel was recontoured for female anatomy based on crew feedback. Checkout of the station unit concluded in November 2021, and NASA reported its operational status as a work in progress through 2024.

To save mass and volume on a deep space vehicle, the Orion unit was designed as largely zero fault tolerant. On Artemis II in April 2026, a controller fault stopped urine collection hours after launch, and later in the

mission frozen urine appeared to block the vent line. The crew used contingency urine containers that lack the airflow feature needed in microgravity.

05 Commercial vehicles

SpaceX redesigned the Crew Dragon toilet after a problem during the Inspiration4 mission in 2021, when a urine line separated and released fluid beneath the cabin floor. During the flight, a fan fault in the waste management system set off an alarm, and the crew reported that they did not notice the contamination until after landing. The redesign replaced the joint with a welded assembly before the next crewed flight. The case demonstrates that commercial programs encounter the failure modes of government programs, since both rely on airflow, plumbing joints and controllers within tight volume limits.

The same capsule, Crew Dragon Resilience, flew the Polaris Dawn mission from 10 to 15 September 2024. Because Dragon has no airlock, the whole cabin was depressurized for the first commercial spacewalk on 12 September 2024, and SpaceX added oxygen supply and a nitrogen repressurization system for it. Every system in the cabin, including the waste hardware, was therefore exposed to vacuum. As private missions take on longer and more demanding profiles, the waste system has to be specified for each mission profile, with the same scrutiny given to life support and suits.

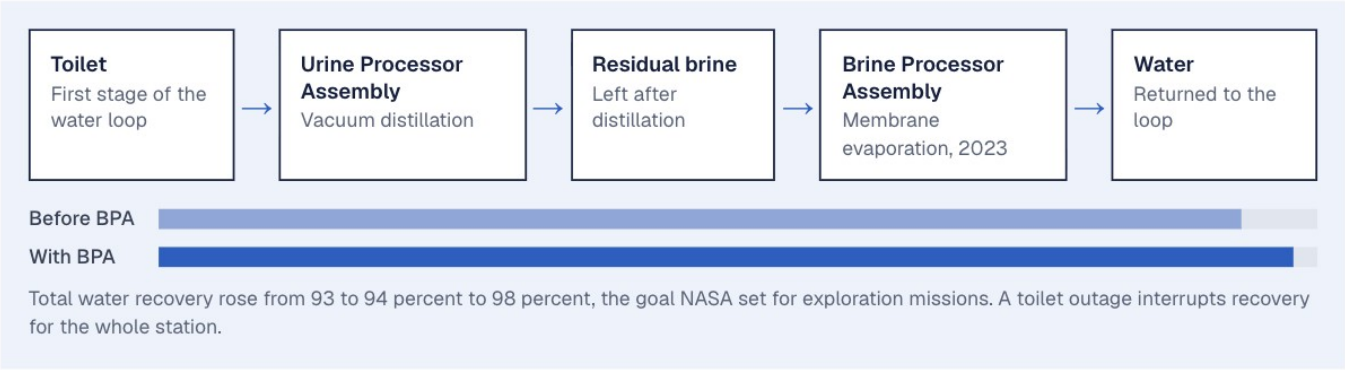
EXHIBIT 3 · SELECTED WASTE SYSTEM EVENTS, 1969 TO 2026

1969	●	**Apollo 10**	Solid waste escapes containment in the cabin
1973	●	**Skylab**	First toilet to use airflow for collection
2008	●	**ISS Zvezda**	Urine fan fails; spare pump flown on a Shuttle
2009	●	**ISS Destiny**	Toilet floods with thirteen people aboard
2010	●	**ISS**	Calcium deposits clog the liquid waste line
2020	●	**UWMS**	Delivered to the station at a reported $23M
2021	●	**Inspiration4**	Urine line separates beneath the cabin floor
2024	●	**ISS UPA**	Pump fails; spare flies on Starliner, 5 June
2026	●	**Artemis II**	Controller fault stops urine collection, April

06 Water recovery from waste

The station recovers water from urine through the Urine Processor Assembly, which uses vacuum distillation and produces a residual brine. In 2023 the Brine Processor Assembly, which evaporates water from that brine through a membrane, raised total water recovery from between 93 and 94 percent to 98 percent, the goal NASA set for exploration missions. Feces contain up to 75 percent water by mass, and NASA continues to study recovery of that water. The toilet therefore functions as the first stage of the water loop, and a toilet outage interrupts recovery for the whole station.

EXHIBIT 4 · WATER RECOVERY FROM URINE ON THE INTERNATIONAL SPACE STATION



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07 Solid waste and trash

Long missions generate roughly one kilogram of trash per astronaut per day, mostly packaging, clothing, food residue and hygiene wipes. Plastic food packaging accounts for roughly 21 percent of solid waste on the station. Crews compact this trash by hand and load it into cargo vehicles that burn up on reentry, a method that consumes crew time and offers little value far from Earth.

Among the alternatives NASA has developed, the Heat Melt Compactor uses heat and pressure to compact plastic waste into stable tiles and to recover water. Trash to Gas systems such as OSCAR convert waste into a ventable gas stream, which reduces stored mass and volume. Jettison studies for Mars transit, including a 2023 comparison of Trash to Gas with jettison through a trash lock (ICES-2023-047), evaluate ejection of waste from the vehicle, which reduces propellant demand. A Mars mission may extend from 800 to over 1,100 days, so each of these options has a large logistics effect.

08 Recurring failure modes

Across sixty years of hardware, failures cluster in four modes.

EXHIBIT 5 · FOUR RECURRING FAILURE MODES

1 · MECHANICAL Fans, pumps and gas liquid separators that operate under high duty cycles and contact corrosive fluids.	2 · CHEMICAL Pretreatment acid, calcium precipitation and freezing in vent lines exposed to vacuum produce blockages.
3 · CONTROL LOGIC As on Artemis II, where a single controller fault disabled urine collection for a whole crew.	4 · INTERFACE WITH THE BODY Funnel geometry, seat design and airflow rate determine whether waste reaches the system at all, a factor that affects female crew members in particular.

09 Organizational causes

The recurrence also has an organizational cause. Programs on tight schedules tend to extend heritage

systems, and waste hardware receives attention late in the design of a vehicle. Anthony Sims described this problem in his interview with the Lab:

> "Everyone wants to design the cupola. Nobody wants to own the toilet. But the toilet is the thing that decides whether a hundred people can actually live up there."
>
> ANTHONY SIMS · FORMER PRINCIPAL OF INDUSTRIAL DESIGN, SPACEX

A habitat program assigns lead designers to visible spaces such as the cupola, and waste hardware becomes a subsystem procured from a supplier late in the schedule. The result is a fixture designed around the hardware and its constraints, and the crew adapts its body to the machine.

Grant Anderson, cofounder of Paragon Space Development, observed a related barrier during decades of work on life support. In conversations with the Lab, he described how rivalry between NASA centers slowed the transfer of ECLSS technology, a pattern he witnessed between Marshall and Johnson Space Center. He also characterized the gap between TRL 4 and TRL 6 as a policy problem, in which mature hardware stalls because programs lack a mechanism to adopt it.

10 Requirements for future habitats

The next generation of crewed habitats places waste systems in three distinct operating environments. Commercial stations in low Earth orbit will host rotating crews of private astronauts and government customers, and their operators must meet NASA crew health standards with small teams and tight budgets, so toilet reliability becomes a commercial risk as well as a crew health risk. Lunar surface habitats will operate in one sixth gravity with abrasive dust, limited resupply and long intervals between repairs, and since current designs assume microgravity airflow, a lunar toilet requires a design and test campaign of its own, a question NASA opened publicly with the Lunar Loo Challenge in 2020. Mars transit vehicles will operate for two to three years without resupply or return, which makes water recovery, trash processing and spares the main drivers of system mass.

EXHIBIT 6 · OPERATING ENVIRONMENTS FOR FUTURE WASTE SYSTEMS

	Commercial LEO station	Lunar surface habitat	Mars transit vehicle
Gravity	Microgravity	One sixth gravity	Microgravity
Resupply	Regular cargo flights	Limited	None for 2 to 3 years
Main risk	Reliability as commercial and crew health risk	Dust, long repair intervals, untested airflow design	Water recovery, trash and spares drive system mass
Open question	Meeting NASA standards with small teams	A toilet designed and tested for partial gravity	Recovery or jettison of waste

Based on this review, the Lab proposes six requirements that apply across these environments.

01 Programs should assign the waste system a design owner from the first phase of the architecture, with authority equal to the owners of the main living spaces.

02 Hardware should include fault tolerance in controllers and fans, with crew serviceable parts and spares sized to the resupply interval of each destination.

03 Designers should validate the interface between body and fixture with diverse body types in microgravity, partial gravity analogs and parabolic flight.

04 Vent and dump lines should avoid exposure to freezing conditions, or the design should replace overboard venting with full recovery.

05 Programs should treat the toilet, water recovery and solid waste processing as one integrated system, with targets for water recovery, trash volume and crew time.

06 The system should be evaluated with equivalent system mass across mass, volume, power, cooling and crew time.

Grant Anderson has proposed two policy measures that would help such technologies reach flight. Under the first, NASA would advance the top five SBIR Phase II performers to Phase III and flight, at roughly $3 to $5 million each within about two and a half years. Under the second, primes such as KBR would direct about 10 percent of a contract toward technologies at TRL 4 to 7, chosen from a list of candidates. He frames this as a “war footing” push from the top of the agency, citing the speed of development during the Second World War.

[REFERENCES]

1. Sims, A. (2026). Interview with A. Prosina, Stellar Amenities Lab.
2. Anderson, G. (2026). Conversations with A. Prosina, Stellar Amenities Lab.
3. McKinley, M. K., Borrego, M. A., and Darmetko, J. (2024). NASA Exploration Hardware Status and Crew Feedback from Artemis 2 Demonstration. ICES 2024 071. NTRS 20240007295.
4. NASA and Collins Aerospace (2023). NASA Exploration Toilet On Orbit Results and Impact on Future Missions. NTRS 20230005900.
5. NASA and Collins Aerospace (2025). Universal Waste Management System, ICES 2025 094. NTRS 20250004005.
6. NASA Ames Research Center (2004). Compaction of Space Mission Wastes. NTRS 20040021352.
7. NASA (2020). Performances of the Heat Melt Compactor System in Various Operational Scenarios. NTRS 20205004360.
8. NASA (2022). Suborbital Testing of the OSCAR Trash to Gas System. NTRS 20220009118.
9. NASA (2023). Benefits of Trash-to-Gas versus Jettison of Waste via Trash-Lock for Mars Transit. ICES-2023-047, 52nd International Conference on Environmental Systems, 16–20 July 2023, Calgary, Canada. NTRS 20230000658.
10. NASA (2023, June 20). NASA Achieves Water Recovery Milestone on International Space Station.
11. CNN (2026, April 4). More than halfway to the moon, the Artemis II astronauts grappled with a toilet problem.
12. CNN (2021, September 25). SpaceX had a problem onboard the first all-tourist flight. It could have been much worse.
13. SpaceNews (2024, June 5). Starliner lifts off on crewed test flight.
14. CNN (2024, July 10). NASA’s Boeing Starliner test flight astronauts discuss spacecraft problems.

15. SpaceNews (2024, September 12). Polaris Dawn astronauts perform spacewalk.

16. Smithsonian Magazine (2020). NASA Just Sent a New $23 Million Space Toilet to the International Space Station.

17. Space.com (2008). Space Station Toilet Breaks Again.

18. NBC News (2009). Toilet broken on crowded space station.