# Development of a Planetary Water Treatment System

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**As NASA prepares for human missions beyond the International Space Station (ISS), NASA personnel have begun development of a water treatment system that is optimized for operation on the Moon and Mars. This system will take advantage of the partial gravity of surface-based habitats while minimizing resupply mass and ensuring optimum reliability. An overview of expected water uses, waste streams, and architectures for a partial gravity water recovery system (WRS) is presented and compared to the WRS on ISS. This paper summarizes the current progress of evaluating various technologies and architectures for the potential mission profiles currently being considered.**

## Nomenclature

*AES* = Advanced Exploration Systems
*CCAA* = Common Cabin Air Assemblies
*CM* = crew member
*COTS* = commercial off-the-shelf
*DMSD* = dimethylsilanediol
*ECLSS* = environmental control and life support systems
*EVA* = extravehicular activity
g = intensity of gravity force per unit mass, N/kg
*GAC* = granular activated carbon
HC = humidity condensate
*HEOMD* = Human Exploration and Operations Mission Directorate
*ISS* = International Space Station
*ITS* = inorganic total solids
*LEO* = Low Earth Orbit
*MF* = multifiltration
·OH = hydroxyl radical
OD = oxygen demand
*PGH* = Partial Gravity Habitat
*PHP* = personal hygiene product
*TCCS* = Trace Contaminant Control System
*TOC* = total organic carbon
*UPA* = urine processor assembly
*WHC* = waste & hygiene compartment
*WPA* = water processor assembly

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# I. Introduction

During the coming decades, NASA has ambitious plans for humans to explore and live in distant destinations beyond low Earth orbit (LEO). Such missions will require robust and reliable environmental control and life support systems (ECLSS) and engineering systems operating under a diverse range of new challenging conditions. Mission enabling technologies for extraterrestrial locations will build and expand on the experience of the International Space Station (ISS), which has been continuously occupied during the two decades since November 2, 2000. Designs of ECLSS for future human missions will incorporate the ISS microgravity operational experiences with state of the art, small-scale, terrestrial technologies that enable partial gravity habitats (PGHs) with functioning and integrated thermal, food, air, water, and waste systems.

Key differences in environmental parameters of LEO and partial gravity missions include variations in gravity fields, temperatures, pressures, solar and ionizing radiation. Key engineering constraints on ECLSS designs include launch mass, transit times, resupply limitations, electrical power supply, crew time, and fiscal budget. Current roadmaps include lunar visits and habitats in the 2020's and Mars missions in the 2030's.[1,2] NASA's Advanced Exploration Systems (AES) Division within the Human Exploration and Operations Mission Directorate (HEOMD), develops, tests, and verifies ECLSS system components of transit vehicles, orbiting stations, and foundational ground systems.[3] A fundamental part of all of these engineering systems is a working water system that stores, transports, treats, and reuses water to support human health and crew activities in support of mission objectives in various deep space destinations.

The ISS Water Recovery System (WRS) provides a well-established baseline habitat architecture to provide knowledge and a technological starting point for development of future foundational water management technology systems for crew populations of less than ten. Two key differences between the ISS and a partial gravity habitat (PGH) WRS include: 1) the strength of the gravity field and 2) additional waste streams within lunar and planetary surface habitats compared to ISS. New waste streams of a PGH relative to the ISS baseline water cycles are expected to include expanded hygiene activities utilizing sinks and showers, and possibly a water-based laundry. Increased high purity water demand for more frequent EVAs is also expected to support extensive planetary exploration by the crew living in a land-based habitation.[1] The surface EVAs are a potential source of regolith particulates within the PGH. The crew occupancy schedules (intermittent crewed and uncrewed periods of time) of PGHs are under development, but are expected to differ from the continuous occupation of ISS by crew. Moreover, transit times for crew and resupplies will be orders of magnitude different between ISS (hours), the Moon (days), and Mars (months). Although not a focus of this paper, other difference between ISS and planetary habitats are the available power supply by solar radiation and the levels of ionizing radiation within the habitat.

This paper focuses on the development of partial gravity water recovery systems in foundational, surface habitats on the Moon and Mars. An overview of expected water uses, waste streams, and architectures for a PGH-WRS is presented and compared to the LEO-WRS on ISS. The goal of this paper is to define the waste streams (Section II) and present critical parameters to guide treatment technology trains to be tested (Section III).

# II. Waste Streams

In this section we define the expected quantities and compositions of the waste streams within a partial gravity, surface habitat on the Moon ($g = 1.62$ N/kg) or Mars ($g = 3.71$ N/kg). The four main waste water streams to be defined are humidity condensate, urine, hygiene, and laundry. Under current practices on ISS, the WRS receives inputs from two dominant liquid waste streams: humidity condensate and urine. Therefore, the ISS WRS experiences for the last decade provide expected flowrates and water quality of humidity condensate and urine for the conditions on ISS. Sabatier product water is a third waste stream that is transported to the Water Processor Assembly (WPA). The water in fecal matter (~75 to 80% by mass) is approximately 120 grams per crew member per day (120 g/CM-day), representing 2 to 3% of total water emissions from the body. However, fecal matter collection does not support water recovery,[4] though technologies are under development to recover both water and nutrients from fecal matter and urine in missions beyond ISS.[5]

## A. Humidity Condensate

Regardless of a habitat's location, humidity condensate will always be available for reuse. The continuous production of HC with low salt content make it well suited for treatment and approximately 100% recovery to potable water. For example, between November 2, 2000, and February 1, 2020, 21,165 liters of water from the cabin atmosphere had been recovered by the SRV-K system in the Russian segment.[6]

### *1. Humidity Condensate Production Rates*

On ISS, humidity condensate is condensed from water vapor by the Common Cabin Air Assemblies (CCAAs). Water vapor is principally from respiration and evaporated perspiration from crew (crew latent water), with some water vapor coming from auxiliary sources (e.g. plant growth, payloads). A humidity condensate production rate per crew member of 1.95 kg/CM-day based on the HIDH 4 person crew is used for ISS.[7] This value increases to 2.99 kg/CM-day for four crew members with each representing the upper 75th percentile based on the full range of possible crew body mass, hydration, and daily activities. Calculated ISS HC production rates for the United States Orbital Segment crews have varied in the range of 1.3 to 2.4 kg/CM-day.[8] NASA's Life Support Baseline Values and Assumptions Document, BVAD, cites crew latent humidity condensate production as 2.27 kg/CM-day for ISS and for an early planetary base.[9] In addition to crew body latent water, 0.4 kg-water/CM-day is assumed for hygiene practices on ISS, of which about 0.33 kg of water is estimated to evaporate and 0.07 kg is lost to wet trash.[4]

### *2. Humidity Condensate Water Quality*

The water quality of humidity condensate on ISS is dominated by low-molecular weight, organic compounds that partition from the atmosphere into the condensed water in accordance with Henry's Law.[10] Thus, the HC water quality is interconnected with the air-phase trace contaminant control system (TCCS) and the aqueous solubility of volatile molecules. The compounds in HC are volatile compounds emitted by the crew metabolism and off gassing from hardware. In addition to organics, inorganic carbon and ammonium ions are also present, as well as some metals (nickel, zinc, and silver) leached from the wetted surface on the condensing heat exchanger. pH is typically neutral, averaging 7.2 ± 0.4.[11] The abundance of small molecular weight organic compounds makes humidity condensate a biologically active solution, especially at the ambient temperature of the WPA wastewater tank.

A number of ersatz formulations have been used for simulating ISS humidity condensate in ground testing. These include an early formulation based on data obtained from Shuttle and Spacelab missions and ISS U.S. Lab Condensates Expeditions 2 through 17.[12] The ersatz recipe derived from the returned samples HC samples was based on including compounds with a concentration greater than 0.5 mg/L out of more than 150 compounds that were identified and measured. The organic HC constituents consisted of 26 compounds for a total mass concentration of 453 mg/L and a total organic carbon concentration of 226 mg-C/L. The inorganic HC components included four cations (potassium, sodium, ammonium, and calcium) and four anions (chloride, fluoride, sulfate, bicarbonate) ions for a total inorganic solids concentration of 131 mg/L, dominated by 125 mg/L of ammonium bicarbonate. The returned HC samples demonstrated a wide range of TOC from 51 to 436 mg/L. Ten compounds in the ersatz formulation were present at concentrations greater than 10 mg/L (4.4 mg/L as TOC). These compounds contribute approximately 90% of the total dissolved solutes and TOC in the ersatz and the humidity condensate generated in the space vehicles.

A more recent study of 54 humidity condensate samples returned from ISS over 15 years between March 2001 and February 2016 revealed a TOC average of 171 mg-C/L (standard deviation of 97 mg/L) and a total inorganic carbon, TIC, average of 34 mg-C/L (standard deviation of 14 mg/L).[13]

NASA, Boeing, and Collins Aerospace personnel developed an ersatz of the WPA wastewater for ground testing.[14] The WPA wastewater represents a nominal combination of HC and urine distillate from the UPA, with approximately equal volumetric mixtures of condensate (~50%) and distillate (~50%). The TOC of the WPA Wastewater ersatz was 40 mg-TOC/L, indicating the biofouling potential of the waste water. Dissolved oxygen has been estimated to be the limiting factor in biofilm formation.[15] Some leached metals from wetted surfaces may also contribute to inhibition of biodegradation. Testing is ongoing to verify oxygen as the limiting substrate and other nutrient limitations for bacterial degradation of organics in the WPA influent. In this paper, we introduce the concept of oxygen demand of all the waste streams as a useful parameter to assess biofilm formation potential and the appropriate oxidation technologies to stabilize waste waters.

A new refractory organo-silicon compound of interest was discovered in humidity condensate in 2010 and was identified to be dimethylsilanediol, DMSD ($C_2H_8O_2Si$). DMSD is 26.1% carbon and 30.5% silicon by mass. The covalent bond between carbon and silicon atoms in DMSD is not found in nature, making it challenging to cleave by traditional treatment processes. DMSD has low toxicity, but its organic carbon content can exceed the bulk TOC limit for potable water if DMSD breaks through WPA's MF beds and the Catalytic Reactor. Approximately 2 to 4% of volatile methyl siloxanes' (VMS) silicon emitted from surfaces and personal care products into the ISS cabin atmosphere (total volume of ~810 $m^3$) are estimated to be converted to DMSD within the ISS habitat.[16] Total VMS emissions are estimated to be between 500 and 2500 mg-Si/day. The transformations from VMS to DMSD are thought to take place principally in the gas phase by reaction of VMS with hydroxyl radicals, ·OH.[11,16] Surface hydrolysis reactions on the condensing heat exchanger surfaces are also a potential source of DMSD in humidity condensate. In 2020, the ISS program instituted a siloxane management plan to minimize hygiene products containing siloxanes used by the crew. In addition, twenty-one activated carbon filters (Charcoal HEPA Integrated Particle Scrubbers, CHIPS) were installed in HEPA filter locations throughout the US Segment in Nodes 1, 2, and 3, US Lab, and the Airlock. Air flow was 114 $m^3$/hour through each CHIPS filter (~2,394 $m^3$/hour total).[17] The combination of air-phase VMS removal provided by the CHIPs filters and the siloxane management plan (utilizing siloxane-free crew hygiene products) resulted in a reduction in DMSD concentrations in humidity condensate from about 40 mg/L to less than 20 mg/L as of October 20, 2020.[18] DMSD is found at lower concentrations in the Russian Segment's humidity condensate due to the effect of temperature on Henry's Law equilibrium constant for DMSD.  Water condenses at 4.4 °C in the US segment and 14 °C in the Russian segment, resulting in increased aqueous concentrations of DMSD (by a factor of about 2) in the US segment's humidity condensate for the same air phase concentrations of DMSD.[11]

### B. Urine

Urine is the most challenging waste stream within a habitat to collect, store, and transform to potable quality. The challenge is due to fact that urine has a salinity (total dissolved solids on the order of 40 gm/L) very similar to seawater, but also contains high levels of biologically active organic carbon (e.g. uric acid, citric acid) and nitrogen (e.g. urea, creatinine, ammonium) compounds. In addition, mucous and squamous cells can be present. Ubiquitous bacterial cells in freshly collected, untreated urine increase in population (e.g. $2 \cdot 10^7$ cfu/mL in 5 hours) and lower the dissolved oxygen concentration to less than 1 mg/L within 24 hours.[19] Urine may be "sterile" within the body, but does not remain so upon leaving the body.

#### *1. Urine Production Rates*

On ISS, average urine production rates based on 24-hour individual urine collection from US Crew for 2010 to 2018 averaged 1.85 L/CM-day with a standard deviation of 0.81 L/CM-day (n = 239).[20] Prior to 2010, the average urine production rate was 1.3 ± 0.5 L/CM-day for 2007 to 2009 (n = 66).  For comparison, the BVAD cites 1.50 kg/CM-day for urine in Planetary Bases.[9]

In October 2009, the UPA experienced a failure due to the precipitation of calcium sulfate (gypsum) at the nominal recovery rate of 85%. One response to this event was to encourage crew to consume more water for health reasons, but also to reduce the calcium concentration in the crew urine. In addition to increasing urine production rates beginning in 2010, this event resulted in the development of a new pretreatment solution to enable 85% recovery from pretreated urine without gypsum precipitation in 95th percentile urinary calcium and sulfate concentrations for crews of three using the Waste & Hygiene Compartment (WHC) for one year of UPA operations on ISS.[21]

In the case of urine collected by the WHC on ISS, urine is diluted with 50 mL of deionized water per flush. The average range of WHC flushes on ISS is between 6 and 9 flushes/CM-day for the 2018 to 2020 timeframe.

#### *2. Urine Water Quality*

A number of publications have summarized the composition of urine.[12,22,23,24,25] Urine's dissolved solids are dominated by urea and sodium chloride. Urea contains nitrogen in its reduced form, N(-3), and carbon in its oxidized state, C(+4). Urea is 20.00% carbon and 46.65% nitrogen by mass. 24-hour urine from males contains 21 grams of urea (10 grams of reduced nitrogen). If urinary volume is 2 L in 24 hours, the urine has a concentration of urea nitrogen of 5 g-N/L. In addition to urea, fresh urine contains reduced nitrogen in the form of organics (e.g. creatinine: 37% N by mass, uric acid: 33% N by mass, histidine: 27% N by mass) and as the ammonium cation. Urea accounts for 80 to 90% of the total nitrogen in urine.

The reduced carbon in urinary organic compounds, along with the reduced nitrogen in urea, organics, and ammonium salts results in a high oxygen demand of urine in the presence of bacteria. The oxygen demand of urine is on the order of 10,000 mg-$O_2$(aq)/L, compared to a typical aqueous concentration of 8 mg-$O_2$(aq)/L. Therefore, urine will quickly lose its dissolved oxygen without aeration or pretreatment to inhibit bacterial respiration.

Although ersatz may be used in early development of emerging technologies, a transition to real urine is critical to capture the realistic challenges of actual urine undergoing the physical and chemical changes associated with water removal from urine: suspended solids (e.g. squamous epithelial cells), mucous, bacteria loading, thousands of metabolites, foaming, and viscosity. Human urine is a biologically active solution with bacterial cells, organic substrates, neutral pH, and nutrients, which quickly becomes a multi-phase fluid, by precipitation and/or odorous gas generation. Real urine with the naturally occurring bacterial loading is the best way to monitor for urea hydrolysis. Urea hydrolysis is caused by the urease enzyme produced by bacteria, which produces ammonia and raises the pH of urine solutions from approximately 6 (fresh urine) to 9 (aged urine). The rate of "aging" of urine is dependent on the cleanliness of the storage containers and the availability of oxygen. Starting with pristine containers, static conditions, and closed to the atmosphere, the time required for urea hydrolysis onset in urine can take on the order of 3 weeks, whereas urea hydrolysis can be spontaneous in containers that have established biofilms from repeated exposure to urine. The result, in addition to the release of ammonia, includes phosphate and urate precipitates and can occur with only 10% of the total nominal urea being hydrolyzed.

The full range of urinary calcium and sulfate concentrations in urine are critical in determining the maximum soluble recovery for worst-case concentrated urine (95th percentile levels) from a crew of 3 using the WHC. For the 2010 to 2014 timeframe with three US crew members using the WHC on ISS, the upper 95th percentile values are 230 mg calcium, 2,200 mg sulfate (as $SO4$), and 3,300 mg phosphate (as $PO4$) per liter of raw urine. It can be concluded that there is a 5% probability of exceeding these values during a UPA concentration cycle during one year of operations on ISS. At the point where % water recovery (%R) from 95th percentile pretreated urine reaches the value of the maximum soluble recovery, $MSR_{95}$, the worst-case urine will become saturated with respect to the first mineral to precipitate, which is gypsum for the ISS UPA conditions with phosphate-based pretreatment.[21,26] The statistical model of 95th percentile urine combined with the solubility of gypsum in returned brines estimates that the maximum soluble recovery (point at which gypsum becomes saturated in brine) from pretreated urine is 92% recovery by volume. This estimate is only applicable to acidified urine (pretreated urine $pH < 2.5$) for a U.S. Crew of 3 (2010 to 2014 urine data) with an oxidizer within the temperature and pressure conditions of the DA on ISS.

### C. Hygiene Waste Water

Although the original design of ISS assumed that 6.8 kg-water/CM-day would be provided for hygiene practices,[27] it was determined that wet wipes and hand towels would be used for personal hygiene to avoid the cost associated with a shower and handwash station. 14,560 wet wipes (COTS) for personal hygiene are launched each year to ISS, with a water content of about 5 grams per wet wipe or 72.7 kg of water. During use of the wet wipes, the relative partitioning of this water into the ISS cabin atmosphere and wet trash is unknown to the authors. Rinseless body wash is used for skin and hair. About 0.4 kilograms of water per person (0.4 kg/CM-day) is assumed for personal hygiene practices on ISS.[4]

In the case of future habitats with partial gravity on the Moon or Mars, the baseline assumption is that additional water will be provided to crew for showering, hand washing, oral hygiene, and shaving. Small amounts of water for dishwashing (e.g. personal drink containers) are also under consideration. Hygiene product quantities and volumetric water flow rates associated with full hygiene practices were defined for the Alternative Water Processor Testing at JSC in 2014, which simulated a crew of four in a planetary base with full hygiene and laundry.[28] Total hygiene water use was 7.25 kg/CM-day. The Devon Island Mars Research Station habitat used 2.2 kg-water/CM-day for hygiene, 2.0 kg-water/CM-day for laundry, and 3.5 kg-water/CM-day for kitchen activities for comparison.

Estimates and measurements of the water quality of habitat hygiene wastewaters have been published.[9,22] Surfactants of the current US crew's baseline body wash are present in a range of 0.5 to 0.6 g/L, with sodium chloride (~200 mg-NaCl/L), and other poorly defined constituent quantities of sweat, sebum, solids, hair, and skin cells.

### D. Laundry Waste Water

In addition to water for hygiene practices, the water required for washing of clothes and towels is a potentially significant load. Optimal detergents and concepts of laundry operation are under development to minimize water volumes and downstream treatment requirements.[29] A water-based laundry has not been operated on ISS, where clothes and towels are used until trashed. Both the volume of water and the physics of operating a washing machine in microgravity with foaming are challenging. In the case of a microgravity laundry machine for a Mars transit mission, the breakeven ESM point for having a water-based laundry was on the order of 13 months for clothes (laundered mass rate of about 0.2 kg-clothes/CM-day), which reduced to 11 months with towels and wipes.[30] Due to the relatively high equivalent system mass, ESM, of water-based laundry compared to hygiene water uses, non-aqueous cleaning of clothes are also under investigation. Similar to personal hygiene activities, personal clothing for diverse mission activities involves many personal preferences and functions, so many human factors and crew input will be required to arrive at an optimal solutions that support crew health and comfort subject to mass and power constraints of the WRS.

The water quality of laundry waste water is dominated by the detergent constituents, including the surfactants, enzymes, polymers, and soils on the clothing (sweat and skin cells). Similar to hygiene waste waters, the laundry waste water contains suspended solids and has foaming properties. Both hygiene and laundry waste waters are dominated by biodegradable organics and are relatively low in inorganic salts and reduced nitrogen (urea and ammonium) compounds compared to urine.

### E. Summary of Waste Streams

Table 1 summarizes the expected nominal daily mass flows of waste water per day for one crew member. The far right column represents the values for testing of PGH water recovery technologies. The PGH waste stream scenario would generate a total of 15.3 kg/CM-day. This value compares to typical ISS waste water mass rates of about 4.3 kg/CM-day. For a crew of four, PGH would need to recovery 61.2 kg/day compared to 17.2 kg/day for ISS WRS operations with a crew of four. The total volume and mass of waste waters to collect, store, transport, and process are increased by a factor of 3.6 in the PGH relative to ISS.

**Table 1** Expected Nominal Daily Mass Flow Rates of Partial Gravity Habitat

| | **Kilogram of Water per Crew Member per Day, kg/CM-day** | | | | |
|---|---|---|---|---|---|
| **Parameter** | **ISS US Segment (2010 – 2018)** | **Devon Island Mars Research Station** | **BVAD (2018) EPB/MPB** | **JSC Alternative Water Processor Test (ICES-2016-57)** | **Planned 2021 PGH-WRS Architecture Testing** |
| **Humidity Condensate** | 1.7 to 3.0 | - | 2.27 / 2.90 | 1.95 | 2.0 |
| **Urine** | 1.6 to 2.2 | - | 1.50 / 1.50 | 1.2 | 2.0 |
| Urinal Flushwater | 0.25 to 0.45 (0.05 kg/flush) | 0 (water-less compost toilet) | 0.5 / 0.5 | 0.3 | 0.30 |
| **Hygiene** | 0.4 | | | | |
| Sinks | - | 0.64 | - / - | 1.0 | 1.0 |
| Shower | - | 1.08 | 1.08 / 1.08 | 6.0 | 6.0 |
| Oral | - | 0.46 | 0.37 / 0.37 | 0.2 | 0.2 |
| Shaving | - | 0.05 | 1.08 / 1.08 | 0.038 | 0.05 |
| **Clothes and Towels Laundry** | - | 1.95 | 0 / 3.54 | 3.75 | 3.75 |
| Dishwasher/Kitchen sink | - | 3.54 | - / - | - | -TBD |
| **Other Streams** | | | | | |
| Sabatier Water | 0.0 to 0.3 | | | | -TBD |
| EVA | - | | | | -TBD |
| Cleaning, Science, Engineering | - | 0.08 | | | -TBD |
| Plant Growth | | | | | -TBD |

The nominal water quantities and qualities of the waste streams are shown in Table 2. Values for the masses of total solids, inorganic solids, reduced carbon, and reduced nitrogen (expressed as Total Kjeldahl Nitrogen, TKN), have been calculated from previously published concentrations in PGH waste streams.[22] For 30 days of operation with a crew of four, the PGH-WRS would receive a total of 1,836 kg of waste water compared to 516 kg for a crew of 4 in the US segment on ISS. Under one year of continuous operations, 22,353 kg of waste waters would be produced in the PGH-WRS scenario compared to 6,282 kg on ISS listed in Table 2.

**Table 2** Mass of Water, Key Constituents, and Occupied Duration by Crew of 4.

| | | Total Waste Water | Total Solids | Inorganic Salts | Reduced Carbon | Reduced Nitrogen | Theoretical Oxygen Demand of Reduced Carbon and Nitrogen |
|---|---|---|---|---|---|---|---|
| **Waste Stream** | **Occupied Duration** | **kg of Waste Water** | **kg of Total Solids** | **kg of Total Inorganic Solids** | **kg of Non-Urea TOC** | **kg of TKN** | **kg-O2(aq)** |
| Humidity Condensate | 1 day | 8.0 | 0.005 | 0.001 | 0.002 | 0.0002 | 0.002 |
| | 30 days | 240 | 0.143 | 0.033 | 0.054 | 0.006 | 0.067 |
| | 1 year | 2,922 | 1.739 | 0.403 | 0.652 | 0.078 | 0.818 |
| | | | | | | | |
| Flushed Urine | 1 day | 9.2 | 0.187 | 0.06 | 0.02 | 0.05 | 0.08 |
| | 30 days | 276 | 5.616 | 1.9 | 0.5 | 1.6 | 2.5 |
| | 1 year | 3,360 | 68.376 | 22.9 | 5.6 | 19.6 | 30.7 |
| | | | | | | | |
| Hygiene | 1 day | 29 | 0.023 | 0.007 | 0.009 | 0.001 | 0.017 |
| | 30 days | 870 | 0.699 | 0.215 | 0.280 | 0.044 | 0.504 |
| | 1 year | 10,592 | 8.506 | 2.616 | 3.413 | 0.534 | 6.133 |
| | | | | | | | |
| Laundry | 1 day | 15 | 0.003 | 0.001 | 0.001 | 0.0002 | 0.002 |
| | 30 days | 450 | 0.082 | 0.032 | 0.028 | 0.006 | 0.057 |
| | 1 year | 5,479 | 0.997 | 0.384 | 0.343 | 0.071 | 0.691 |

## III. Transitioning Water Recovery Systems from ISS Microgravity to Partial Gravity Habitats

### A. Water Recovery System on ISS

#### 1. *Treatment of Humidity Condensate and Urine on ISS*

On ISS, the two water waste streams of humidity condensate and urine are treated separately. The urine is collected in the WHC, where it is pretreated to pH 2 with chromium trioxide and phosphoric acid and delivered to the Wastewater Storage Tank Assembly (WSTA) for processing by the UPA. During UPA operations, the pretreated urine enters the Distillation Assembly, DA, which utilizes vacuum compression distillation to recover 87% of the pretreated urine volume.[31] The maximum soluble recovery without mineral precipitation and scaling is estimated to be 92% for worst-case, 95th percentile pooled urine for 3 US crew members using one WHC for one year on ISS.[21] Between November 21, 2008 and April 20, 2020, the UPA had produced 21,473 kg of distillate with an associated hardware upmass of 2,517 kg (including installed spares). The initial mass of the WRS on ISS when it was installed in 2008 was 1,385 kg. This mass included the combined mass of all UPA and WPA processing and storage tank ORUs, process and power controllers, structural racks, cables and hoses.[32]

Distillate from the UPA is mixed with humidity condensate and stored in the WPA wastewater tank until processing. Approximately equal volumes of humidity condensate and UPA distillate enter the WPA for treatment by the multifiltration beds (activated carbon and ion exchange resins) to remove organic and ionic containments in the waste stream. Low molecular weight organic compounds that are not effectively removed by the MF beds are oxidized to organic acids and carbon dioxide by a catalyst at elevated temperature and oxygen in the catalytic oxidation reactor. An ion exchange bed downstream of the catalytic reactor discharges deionized water with TOC < 3 mg/L to the pressurized, water distribution system feeding the oxygen generation assembly (OGA), the potable water dispenser (PWD) and the WHC (flush water for urine collection).

In the ISS habitat, the vast majority of reduced compounds (electron donors) in the two liquid waste streams are not oxidized by the treatment train. The reduced compounds in urine, which make up over 95% of all reduced compounds on ISS (with <5% of total reduced compounds loading in humidity condensate) are only partially oxidized by the oxidizer in the urine pretreatment. Hence, the system relies on controlling bacteria by physical and chemical means. The oxidizer is strong enough to inactivate bacteria at pH = 2 of pretreated urine and brine, but not strong enough to oxidize urinary organics to inorganic carbon. Instead, intermediate organic compounds, such as carboxylic acids: formic and acetic acid are formed, some of which partition into the distillate, which has a pH of about 4.5 associated with the pK values of these two acids, which also make up the majority of the TOC in the UPA distillate.

The reduced compounds are also problematic by promoting biofilm formation in the upstream sections of the WPA, where the small, low molecular weight (<200 g/mole) volatile organic compounds in condensed water from the atmosphere at 4.4 °C (increasing aqueous-phase solubility of gas phase constituents in the cold water) serve as ideal substrates for bacteria when the water warms to ambient temperature. For example, dissolved oxygen at equilibrium temperature of 4.4 °C is 13 mg-$O_2$(aq)/L in humidity condensate, compared to 8 mg-$O_2$(aq)/l at 25 °C. As mentioned above, dissolved oxygen is thought to be the limiting substrate for biodegradation of the organic compounds in the incoming WPA waste stream, with the oxygen demand of the organics being several orders of magnitude greater than dissolved oxygen concentrations. Both humidity condensate and UPA distillate contain easily degradable organics with an oxygen demand on the order of 100 mg-OD/L. A number of potential ISS flight experiments are being considered to limit the biofilm growth potential including UV radiation, re-configuring the processors to remove organic compounds upstream of the WPA wastewater bellows tank, as well as an upstream bioreactor. An attached growth bioreactor of 24 liters upstream or as part of the wastewater storage tank would treat the humidity condensate flow and organic loading for a crew of 4.[33]

#### 2. *Microgravity Requirements for Gas-Liquid Separation and No Precipitation*

One of the most challenging attributes of operating the WRS on ISS is the strict requirement to avoid multi-phase flow in which bubbles or precipitates block the flow of liquid. Both rotary and membrane gas-liquid separators are used extensively throughout the waste water flow paths of the WHC and WRS. Within the water phase, the sum of all dissolved gas pressures must remain below the liquid fluid pressure in order to avoid two-phase flow (e.g. formation of a bubble). In addition, due to the small diameter of pickup tubes that collect the liquid phase in a spinning rotary separator, no formation of solids or precipitates is allowed while transporting pretreated urine and humidity condensate.

### B. Water Recovery System in a Partial Gravity Habitat

#### 1. *Main Differences between the WRS of Partial Gravity Habitats and ISS*

As the name “Partial Gravity” implies, a major difference between ISS and Partial Gravity Habitats is that Partial Gravity Habitats will have a directional gravity field, similar to Earth but less in magnitude. Thus, gravity-driven flow becomes a possibility to transport liquids. This is expected to simplify toilet design for urine collection. Partial gravity will also simplify gas-liquid and solid-liquid separation processes, lessen complexities of dissolved gas requirements of water and wastewaters (bubbles are allowed in certain locations), and lessen the strict requirement of solids formation (scaling and precipitation are allowed in predetermined locations) in liquids. Utilizing partial gravity fields broadens the suite of potential water recovery technologies to include unit processes used in small-scale water systems on Earth.

The other major difference is in the expected addition of greywaters to the humidity condensate and urine waste streams. All closed habitats that do not vent to space will always have water vapor collection and urine generation. Therefore, in the simplest scenario, a PGH would always have those two waste streams available to convert to potable water. The volumes and composition of those two core waste streams are not expected to change significantly in a PGH relative to ISS. There may be some small increases in production rates of humidity condensate associated with showers and sinks in a PGH.

As described above, the ISS WRS was originally designed and tested to include hygiene waters (~6.8 kg/CM-day), but the challenges of microgravity resulted in hygiene practices that do not generate waste hygiene water. With hygiene waters and associated surfactants and additional organic loading, the WPA was modified and ground tested in the 1990’s with additional levels of filtration and biocide resins (e.g. iodine) to control bacterial growth and manage solids associated with hygiene waters.[34]

The addition of hygiene waters from sinks, shower and a clothes washing machine results in a significantly larger volume of wastewaters (Table 3) with a different composition as new inputs to a PGH-WRS. Simulation models and trade studies are underway to optimize the down selection and testing of PGH waste streams in 2021 consisting of humidity condensate, urine, hygiene waters, and laundry waste water. Testing with realistic full-scale waste streams (simulating daily production of humidity condensate, real urine, greywaters for crews of 1, 2, 3, 4 persons) will provide experimental data on water and microbial quality changes by treatment processes to improve simulation models and optimization tools of various PGH-WRS system configurations.[22]

The current estimates for nominal PGH waste water flow rates and key treatment-determining constituents are listed in Table 3. Technical innovations and optimized hygiene and laundry operations and technologies are expected to decrease water volumes required for those new PGH crew activities. The four columns on the right hand side of Table 3 serve as a framework for designing the PGH-WRS and defining the treatment requirements of technologies to convert each waste stream to potable water. The parameters for each waste stream are: the average daily volumetric flowrate, the inorganic total solids concentration, the total oxygen demand of reduced carbon species, and the total oxygen demand of reduced nitrogen species. The high concentration values of the oxygen demand of reduced nitrogen emphasizes that the waste water is a high-strength nitrogen waste water due to urine and the lack of significant dilution relative to domestic waste waters.

**Table 3** Daily Mass Flows of Waste Streams and Key Constituent Concentrations

| | ISS Daily Flow Rate per Crew Member for comparison | PGH Daily Flow Rate per Crew Member | PGH Total Daily Flow Rate for crew of 4 | Inorganic Solids Concentration | Oxygen Demand of Reduced Carbon Concentration | Oxygen Demand of Reduced Nitrogen Concentration |
|---|---|---|---|---|---|---|
| **Waste Stream** | **ISS L / CM-day** | **PGH L / CM-day** | **PGH L / day** | **g-ITS / L** | **g-OD(C) / L** | **g-OD(N) / L** |
| Humidity Condensate | 2.0 | 2.0 | 8.0 | 0.14 | 0.25 | 0.12 |
| Flushed Urine | 2.3 | 2.3 | 9.2 | 6.8 | 1.9 | 23.5 |
| Hygiene | 0.0 | 7.25 | 29.2 | 0.25 | 0.36 | 0.22 |
| Laundry | 0.0 | 3.75 | 15 | 0.07 | 0.07 | 0.06 |
| Total | 4.3 | 15.3 | 61.2 | 1.2 | 0.5 | 3.7 |

Tables 3 and 4 provide a framework to guide selection of treatment technologies. The associated treatment steps under development for treating the PGH waste water streams defined in Table 2 and Table 3 are listed in Table 4. Water quality parameters in Table 3 (inorganic solids, oxygen demand of reduced carbon, and oxygen demand of reduced nitrogen) will be checked during testing in 2021. The mix-n-match options of Table 4 technology configurations will be evaluated as they transform the waste streams to potable water. The duration of simulated PGH day-to-day waste water production and subsequent treatment operations to match pending mission durations will be in increments of 1 month in order to allow extrapolation to longer mission durations on the order of years.

**Table 4** Components and Unit Processes of Partial Gravity Water Recovery Systems being Tested in 2021. Underlined technology options are in active testing during 2021.

| **Waste Stream, Nominal Flow for Crew of 4** | **Upstream Generation, Collection, Transport, Storage** | **Pretreatment** | **Primary Treatment, stabilization of reduced carbon and nitrogen species** | **Desalination, removal of ions and solutes** | **Post Treatment to Potable Standards** | **Brine Dewatering** |
|---|---|---|---|---|---|---|
| Humidity Condensate<br>8.0 L/day | CCAAs.<br>WRS Storage Tank or Direct to Treatment Loop.<br>DMSD present in 5 to 40 mg/L concentration.<br>At equilibrium with Atmosphere. Some leaching of metals. | No Pretreatment. UV. Bioreactor. Chemical. | EO, Bioreactor. Or modified Physical/Chemical Treatment (biofilm prevention) | RO Membranes. Distillation: Membranes (MD) or Phase-Change (VCD).<br>CDI.<br>MF beds. | Cat Reactor. MF Beds. Filtration, UV, and/or Biocide. To Water Bus. | BPA or equivalent if brine generated. |
| | ⇩⇧ mixed or segregated | | | ⇩⇧ mixed or segregated | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Hygiene<br>29.2 L/day | Sinks. Shower. Greywater Storage Tank or Direct to Treatment Loop. | No Pretreatment. UV. Bioreactor. Chemical. | EO, Bioreactor. Super Critical Water Oxidation Or modified Physical/Chemical Treatment (biofilm prevention) | RO Membranes.<br>Distillation: Membranes (MD) or Phase-Change (VCD).<br>CDI.<br>MF beds. | Cat Reactor. MF Beds. Filtration, UV, and/or Biocide. To Water Bus. | BPA or equivalent if brine generated. |
| | ⇩⇧ mixed or segregated | | | ⇩⇧ mixed or segregated | | |
| Laundry<br>15 L/day | Washing machine. Greywater Storage Tank or Direct to Treatment Loop. | No Pretreatment. UV. Bioreactor. Chemical. | EO, Bioreactor. Super Critical Water Oxidation Or modified Physical/Chemical Treatment (biofilm prevention) | RO Membranes.<br>Distillation: Membranes (MD) or Phase-Change (VCD).<br>CDI.<br>MF beds. | Cat Reactor. MF Beds. Filtration, UV, and/or Biocide. To Water Bus. | BPA or equivalent if brine generated. |
| | ⇩⇧ mixed or segregated | | | ⇩⇧ mixed or segregated | | |
| Urine<br>9.2 L/day | New PGH Toilet. Urine-Fecal Separation.<br>Urine stabilization and/or transport to Treatment. | No Pretreatment. UV. Bioreactor. Chemical: $H_2O_2$. | EO, Bioreactor. Super Critical Water Oxidation, Physical/Chemical Treatment (urea hydrolysis management) | Distillation: Membranes (MD) or Phase-Change (VCD).<br>CDI.<br>MF beds. | Cat Reactor. MF Beds. Filtration, UV, and/or Biocide. To Water Bus. | BPA or equivalent if brine generated. |
| | | | | | | |
| Total<br>61.4 L/day | | | | | | |

### 2. *Waste Sources and Upstream Interfaces*

The upstream interfaces and volumes for a crew of 4 for humidity condensate and urine will be similar in a PGH relative to ISS. In the case of HC, some alternative CCAA designs and coatings are being considered. A complete and simplified redesign of the ISS microgravity toilet and integration with the WRS of a PGH is expected to take advantage of partial gravity. The collection, transport, and possible storage of the greywaters streams will be a new addition to the traditional sinkless and showerless ISS. Deciding on the number, design, and locations of sink(s), shower, and laundry machine with associated supply (potable water) and collection conduits and storage will require detailed analyses and testing, heating of the hygiene water. Studies are underway to identify the stability of hygiene waters and laundry waters to determine if stabilization or pretreatment is required. Whether urine is pretreated or goes directly into the primary processor by integration with the toilet is another optimization decision to be made.

### 3. *Segregated versus Combined Waste Streams*

A key decision in minimizing overall WRS mass and maximizing reliability is whether to combine waste streams or keep them separate prior to the primary processors. The waste stream volumes and water qualities are different in inorganic salts, organic carbon, and reduced nitrogen as defined in Table 3. The most distinct and challenging waste stream is the urine, which requires significant desalination and oxidation-reduction stabilization compared to the other waste streams. Urine has about 30 times more inorganic salts and about 50 times more reduced compounds in terms of oxygen demand than the other waste streams. Therefore, urine separation is a reasonable approach. But the unique composition of humidity condensate relative to the hygiene/laundry streams also warrants consideration of separate treatment approaches. Despite additional mass requirements and complexities, separate treatment trains provide independent redundancy if one treatment process fails.

### 4. *Primary Treatment – Oxidation-Reduction Stabilization*

All of the various waste streams contain various types of reduced compounds and are well suited for oxidation of those organic and nitrogen compounds to prevent microbial fouling in downstream desalination systems. The two main types of REDOX stabilization processors are bioreactors and electrochemical oxidation. These two technologies or possible hybrid systems are being tested in 2021. Both fixed film and suspended growth aerobic bioreactor systems are to be tested on combined and segregated streams of the PGH. Bioreactors offer natural processes that synch with the crew's water, oxygen, carbon, and nitrogen cycles with little off gasing. In addition, the power requirements for bioreactors is low. Bioreactors have minimal resupply needs, with bioreactors treating simulated habitat wastewaters for three continuous years. The disadvantage of bioreactors are their size (retention time on the order of days) and their startup time (on the order of days or weeks, depending on the incoming organic loading). Inoculation methods are being optimized to address this limitation.

In the other extreme is electrochemical oxidation, EO, by direct contact with an anode and a cathode. EO provides immediate oxidation by production of reactive oxygen and chlorine species, such as hydroxyl radical and chlorine. Promising results have been published for an EO system treating real urine with an anode of boron-doped diamond and a tungsten cathode operating at a current of 30 amps.[35] Although EO has a relatively small footprint, it does require higher energy inputs and produces oxidized gas emissions that must be removed prior to venting to cabin atmosphere.

Other ancillary treatment methods for more advanced habitats with more extensive plant growth and food production include anaerobic bioreactors[5] and supercritical water oxidation.[36]

### 5. *Desalination*

The effluent from bioreactors and EO processors can be desalinated with a wide range of technologies. The main categories involve either membranes or phase-change distillation, such as VCD on ISS. A partial gravity VCD concept for partial gravity with complete dewatering is under development at MSFC. For membrane processes, reverse osmosis and a variety of membrane distillation options are available. Membrane distillation, MD, is capable of higher water recoveries than reverse osmosis, RO, because MD separates species based on their respective volatilities. Therefore, MD has been applied to reject brines in which the osmotic pressure is beyond RO's recoveries. Despite this theoretical potential, MD has limitations similar to RO, mainly due to scaling of membranes at very high recoveries. Capactive Deionization (CDI) is a promising technology that avoids limitations associated with membrane fouling and may provide improved water recovery and permeate quality. Ultimately, the primary issue with RO, MD and CDI is the generation of brine that requires a subsequent treatment process to recover all available water. To avoid brine production, basic heated and/or vacuum distillation to dryness will continue to be investigated, despite higher power requirements and potential scaling of heating elements. Bioreactor effluent has been dewatered to dryness successfully for three months of continuous operation with simulated humidity condensate, urine, hygiene, laundry waste stream.[33]

### 6. *Post Treatment*

The final treatment step for the product water of a PGH-WRS is polishing to meet the potable water and microbial quality requirements. On ISS, the Catalytic Reactor provides oxidation of recalcitrant compounds that were not oxidized nor completely adsorbed in upstream processes. Other advanced oxidation processes are under investigation to meet the stringent TOC standards of potable water (<3 mg-TOC/L).

### 7. *Brine Transport, Dewatering, and Solids Management*

One of the final processes to attain a closed-loop water cycle in a partial gravity habitat is the water recovery from reject brines in upstream systems. The pretreated urine brine from UPA has traditionally been trashed, but this approach is not acceptable for missions beyond ISS in which water resupply is severaly limited. In April of 2021, a Brine Processor Assembly (BPA) was launched to ISS to recover water from the UPA brine. Brine flows into a bladder comprised of an inner hydrophobic microporous membrane and an outer Nafion™ membrane. Heated cabin air is passed over the bag to drive water vapor permeation through the membranes, where it is vented into the cabin atmosphere for recovery by CCAAs. During ground testing, the BPA decreased the final water mass fraction of 90% UPA brine from 66% water (33% solids) to 37% water (63% solids).[17] This represents an increase in mass recovery of available water in pretreated urine (with water mass fraction of 95.4% and 4.6% solids) from 92% by the UPA operating at 90% recovery to an overall 98% recovery of water from pretreated urine for the UPA-BPA systems.

### 8. *Fecal Water Recovery*

Although details of fecal water recovery were not part of this paper and the current year of water recovery testing for partial gravity habitats, technologies are being developed to recover water from fecal matter.[5,37]

## IV. Summary

An evaluation and summary of the quantities and compositions of the four main types of waste streams in future partial gravity habitats has been presented. The urine and humidity condensate flow rates and water quality are based on measured data and operational experience by the crew activities in the U.S. segment of ISS. The baseline assumptions of nominal quantities and composition for two new waste streams, full hygiene and laundry, were quantified. The two new waste streams will quadruple the volumetric production per crew member of total waste water volumes relative to ISS waste water generation rates. Four parameters were introduced to provide a framework for defining the treatment requirements of technologies to convert each waste stream to potable water. The parameters for each waste stream are: the average daily volumetric flowrate, the inorganic total solids concentration, the total oxygen demand of reduced carbon species, and the total oxygen demand of reduced nitrogen species. Technologies that provide the required unit processes to stabilize, oxidize, desalinate, and post-treat the waste streams to potable water were summarized and are undergoing testing in 2021. Continuous, day-to-day testing with simulated PGH waste water streams will provide water quality data on treatment system performance, power, mass, and sizing data of technologies for trade studies to define the most promising technical processes and configurations of architectures for a partial gravity habitat.

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