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A Review of Baseline Assumptions and Ersatz Waste Streams for Partial Gravity Habitats and Orbiting Micro-gravity Habitats

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Highly efficient water management and recovery systems will be required to support human missions beyond the low Earth orbit of the International Space Station (ISS). A review of baseline assumptions for the human activities and associated water cycle in surface, partial gravity habitats and orbiting, microgravity habitats is conducted. The paper reviews and updates ersatz formulations and water flow rates for the main liquid water waste streams of urine, humidity condensate, hygiene, and laundry. Development of a new framework is recommended to coordinate advancement and commonalities of water recovery systems for 30-day crew occupancies under partial gravity with longer term, continuous occupancy in surface or orbiting microgravity habitats and the Mars transit habitat.

Nomenclature

AES	=	Advanced Exploration Systems
BVAD	=	Baseline Values and Assumptions Document
CCAA	=	Common Cabin Air Assemblies
CM	=	crew member
ConOps	=	concept of operations
DMSD	=	dimethylsilanediol
DWI	=	drinking water intake
ECLSS	=	environmental control and life support systems
ESM	=	equivalent system mass
FWR	=	fecal water rate
g	=	intensity of gravity force per unit mass, N/kg
HC	=	humidity condensate
ISS	=	International Space Station
IWR	=	ingested water rate
LEO	=	low Earth orbit
MGH	=	Microgravity Habitat
MWR	=	metabolic water rate

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N	=	newton
PGH	=	Partial Gravity Habitat
TEE	=	total energy expenditure
TOC	=	total organic carbon
UPA	=	urine processor assembly
WHC	=	waste and hygiene compartment
WPA	=	water processor assembly
WRS	=	water recovery system
WTR	=	water turnover rate

I. Introduction

Highly efficient water management and recovery systems will be required to support human missions beyond the low Earth orbit (LEO) of the International Space Station (ISS). The optimal design of future water recovery systems (WRS) will rely on accurate estimates of pending mission requirements and baseline assumptions. This paper focuses on the evolving assumptions and expected conditions associated with the water cycle within a partial gravity habitat (PGH) and how the PGH requirements differ from an orbiting or transit microgravity habitat (MGH) such as ISS. We provide updated values on the flowrates and composition of wastewater streams expected in a PGH, with emphasis on simulating a PGH on the surface of the Moon. The intent is to define common ersatz formulations and wastewater flowrates for ground testing of potential PGH-WRS technologies. Requirements and assumptions for 30-day crew occupancy are quantified. Updated and significantly lower values for water volumes required for cleaning and reuse of clothes and towels are presented for PGHs.

Several key documents provide a range of basic requirements and guidance for microgravity and partial gravity habitats. These include NASA's Human Integration Design Handbook (HIDH),[1] NASA's Human Factors, NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health, (HFHEH),[2] and NASA's Life Support Baseline Values and Assumptions Document, (BVAD).[3]

A. Human Water Cycle

At the core of a space habitat's air and water cycles are the crew's metabolic processes and their physical activities. The range of mass inputs and outputs of water for a crew member has been summarized.[4] The human body partitions consumed water into four main output "streams" based on a number of environmental conditions and activities. Consumed water consists of water in beverages and water in food. Input of water into the body by transcutaneous and inspired pathways is on the order of 20 to 40 grams/CM-day,[5] and considered negligible relative to input of consumed water. An additional, internal source of water is metabolic water production from the aerobic oxidation of organic matter. The four main output water streams from the body are urine, feces, respiration, and perspiration. The water turnover rate (WTR) for humans, in liters/day, is strongly correlated to total energy expenditure (TEE, kcal/day), physical activity, ambient temperature and humidity, and fat free mass.[5] The average daily WTR for humans is on the order of 4 kg/day. Water consumption from food and liquids, which is modulated by thirst to maintain homeostasis, correlates with metabolized energy (TEE). Based on a study of isotope depletion measures of water turnover in 160 females and 149 males, humans consume an average of 1.52 ± 0.42 g-water/kcal, which is also equivalent to the water/energy ratio in human milk (1.5 ± 0.2 g-water/kcal). Water intake also was linked statistically to dry food matter intake, with an average value of 6.8 ± 2.0 g-water/g-dry food. Increased physical activity results in increased water loss to perspiration, decreased water in urine, and increased fecal water content relative to sedentary activity. Hence, water inputs and the associated quantities and composition of the four human body-generated waste streams in habitats link closely to food composition and intake, physical activity, body mass and composition, and the relative humidity and temperature of the habitat. Water turnover rates did not correlate with age nor sex for this group of humans.[5] The effect of clothing on WTR was not included in this study.

Table 1 is a summary of basic relationships of different parameters with the inputs and outputs of water to the body. Additional values for the water balance for a crew member have been calculated and are available in the HIDH,[1] the BVAD,[3] and by Ewert and Stromgren.[4] The values by Ewert and Stromgren shown in Table 1 assume a heavy exercise regime representative of long-term missions (not short-term transit missions). As demonstrated by the range of values in Table 1, the total body wastewater flow rate (water turnover rate, WTR) attributed to each crew member's physiology varies by a factor of about 2 between 5th and 95th percentile individuals. A general rule of thumb for the human body produced wastewater flow rates are a minimum of 3 kg/CM-day, a maximum of 6 kg/CM-day, and a nominal value of 4.5 kg/CM-day.

All human missions will, at a minimum, have this range of daily mass quantities of water in the waste streams to collect, store, dump, or process and reuse. For the human body emitted water, the respiration and evaporated perspiration (crew latent water) form the crews' metabolic fraction of humidity condensate and the urine forms the other major wastewater stream. Based on water turnover studies of humans, the ratio of crew latent water to urine is variable but close to a value of 1. For sedentary humans, the volume of urine typically exceeds the metabolic humidity condensate, whereas the volume of metabolic humidity condensate exceeds the urine volume for physically active humans.[5] With the addition of water-based hygiene practices and non-human water sources, the waste stream quantities will increase within a habitat relative to the human body contributions. The water quality of the various streams will be summarized in the following sections. The goal of this paper is to define the waste stream assumptions of flow rates and water qualities required to test water recovery systems and subsystems and produce comparable results to down select optimal treatment technologies and architectures for a PGH-WRS.

Table 1 Water Turnover and Metabolic Energy Relationships for One Crewmember's Water Cycle

Parameter (kilograms-water/day)	Equation (from Pontzer[5])	Range of Values, from Ewert and Stromgren 2019[4]
Metabolic Water Rate (kg/day) =	0.00014 TEE (kcal/day)	MWR = 0.28 to 0.60 kg/day $MWR_{baseline}$ = 0.48 kg/day
Ingested Water Rate (kg/day) =	Water Turnover Rate (kg/day) - Metabolic Water (kg/day)	IWR_{5th} = 2.78 kg/day IWR_{95th} = 5.35 kg/day $IWR_{baseline}$ = 3.05 kg/day
Drinking Water Intake (kg/day) =	Ingested Water - Food Water	DWI_{5th} = 1.78 kg/day DWI_{95th} = 3.89 kg/day $DWI_{baseline}$ = 2.79 kg/day
Water Turnover Rate (kg/day) =	WTR = Ingested Water + Metabolic Water = Urine + Perspiration + Respiration + Fecal Water	WTR_{5th} = 3.06 kg/day WTR_{95th}= 5.95 kg/day $WTR_{baseline}$= 4.53 kg/day
Fecal Water Rate (kg/day) =	FWR = WTR - Ingested Water - Metabolic Water - Urine - Perspiration - Respiration	FWR = 0.120 kg/day[6] FWR = 0.225 to kg/day[1] $FWR_{average}$ = 0.170 kg/day

Notes:
Precise value of MWR varies with fat, protein, and fat intakes.
IWR values neglect transcutaneous and inspired water (< 40 g-water/day).
"baseline" = 82 kg male astronaut with 90 minutes exercise/day, TEE = Total Energy Expenditure = 3054 kcal/day baseline.[4]

II. Waste Streams

In this section we expand on 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 main habitat wastewater streams to be defined are humidity condensate, urine, hygiene, laundry, and feces. In this paper, we update baseline assumptions on the PGH wastewater streams from previous values and we provide ersatz compositions of humidity condensate and hygiene waste streams. Fecal matter collection on ISS does not currently support direct water recovery, though technologies are under development to recover both water and nutrients from fecal matter and urine in missions beyond ISS.[7,8] Sabatier water, water in wet trash, food waste, dishwashing, vomit, diarrhea, and menses are not included in this paper, but will be added in the future scenarios where a more detailed water balance is required. More details will also be provided on the range of upstream water sources, such as the water quality of the potable water and any residual disinfectants.

A. Humidity Condensate

Regardless of a habitat's location, humidity condensate will always be available and contain the least amount of contaminants relative to other waste streams. The continuous production of HC with low solute content make it amenable for simple treatment to obtain about 100 % water recovery. However, condensation of water vapor is one of the most energy intensive processes in a habitat. Another challenge is the HC's load of small molecular weight organic compounds provide a readily, metabolized substrate for bacteria to form biofilms in the waste collection tank and in upstream treatment steps.

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, hygiene). A humidity condensate production rate per crew member of 1.95 L/CM-day based on the HIDH 4-person crew is used for ISS.[1] This value increases to 2.99 L/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 L/CM-day. A value of 2 L/CM-day was selected for simulating a partial gravity habitat in this paper. This value is a midrange value between the lower values measured on ISS and the higher physiological human model values from the BVAD and HIDH.

2. Humidity Condensate Water Quality

A humidity condensate ersatz was developed for ground testing by Verostko in 2004 and updated in 2009.[9] These ersatz included an early formulation based on data obtained from Shuttle and Spacelab missions and ISS U.S. Lab Condensates Expeditions 2 through 17. The ersatz recipe derived from the returned HC samples was based on including compounds with a concentration greater than 0.5 mg/L out of the more than 150 compounds that were identified and measured. The organic HC ersatz constituents consisted of 26 compounds for a total mass concentration of 453 mg/L and a total organic carbon concentration (TOC) 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. Zinc and nickel ions originating from wetted materials, were not included. The returned HC samples demonstrated a wide range of TOC from 51 to 436 mg/L.

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).[10] Zinc and nickel were included at average and standard deviation concentrations of 2.49 ± 3.52 mg-Zn/L and 19.61 ± 18.60 mg-Ni/L.

Dimethylsilanediol, DMSD ($C_2H_8O_2Si$), a refractory organo-silicon compound was discovered in humidity condensate in 2010 on ISS and continues to be measured in the humidity condensate.[11] It is of concern due to its ability to breakthrough the current WPA treatment train and exceed the TOC limit of potable water of 5 mg/L TOC.[12]

Table 2 presents an updated humidity condensate ersatz based on the water quality analyses of 30 returned samples from the US segment of ISS collected from 11/17/2009 through 4/17/2019.[13] The updated ersatz contains TOC concentration of 103 mg/L and a total solids concentration of 412 mg/L. Ersatz concentrations represent the upper 75th percentile of the 30 returned samples, except for DMSD (median value used). More detailed instructions on preparing the ersatz and adjusting the final pH are available.[9] The current version of ersatz does not contain bacteria and is also lacking some trace nutrients associated with bacterial growth rate limitations. Investigations are underway to add in trace nutrients, including magnesium, iron, manganese, boron, molybdenum, and copper at reasonable levels based on returned samples from ISS. Humidity condensate water quality is closely linked to many factors including: the air revitalization system, cabin volume, crew population and activities, and the wetted materials composition.

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 total dissolved solids on the order of 40 g/L very similar to seawater, but also contains high levels of nutrients, microbial substrates (e.g., uric acid, citric acid) and nitrogen (e.g., urea, creatinine, ammonium) compounds. In addition, mucous and squamous cells can be present.

Table 2 Humidity Condensate Ersatz for Ground Testing of Water Processors

Inorganic Compounds					
No.	**g/mole**	**Cation**	**Anion**	**μM**	**mg/L**
1	79.06	NH_4^+	HCO_3^-	2,509	198.4
2	124.43	Zn^{++}	CH_3COO^-	121	15.0
3	45.08	NH_4^+	CH_3COO^-	329	14.8
4	117.74	Ni^{++}	CH_3COO^-	50	5.9
5	32.06	NH_4^+	CHO_2^-	91	2.9
6	37.04	NH_4^+	F^-	37	1.4
7	162.11	Ca^{++}	$(HCO_3^-)_2$	8.4	1.4
8	136.09	K^+	$H_2PO_4^-$	4.3	0.6
9	84.01	Na^+	HCO_3^-	4.0	0.3
			Sum of all Inorganic and Organic Ions =	3,154	241
Organic Compounds					
No.	**g/mole**	**Formula**	**Compound**	**μM**	**mg/L**
1	46.07	C_2H_6O	Ethanol	1,449	67
	59.04	$C_2H_3O_2^-$	Acetate	see inorganics	
2	92.17	$C_2H_8O_2Si$	Dimethylsilanediol, DMSD*	401	37
3	76.09	C_3H_8O2	Propylene glycol	357	27
4	32.04	CH_4O	Methanol	204	6.5
5	108.14	C_7H_8O	Benzyl alcohol	135	15
	45.02	CHO_2^-	Formate	see inorganics	
6	62.07	$C_2H_6O_2$	Ethylene glycol	73	4.5
7	58.08	C_3H_6O	Acetone	45	2.6
8	113.16	$C_6H_{11}NO$	Caprolactam	21	2.3
9	60.10	C_3H_8O	2-Propanol (Isopropanol)	17	1.0
10	122.12	$C_7H_6O_2$	Benzoic acid	16	2.0
11	138.16	$C_8H_{10}O_2$	2-Phenoxyethanol	14	2.0
12	162.23	$C_8H_{18}O_3$	2-(2-Butoxyethoxy)ethanol	12	2.0
13	87.12	C_4H_9NO	N,N-Dimethyl acetamide	11	0.9
14	222.24	$C_{12}H_{14}O_4$	Diethylphthalate	5.4	1.2
15	90.20	$C_3H_{10}OSi$	Trimethylsilanol	4.6	0.41
16	44.05	CH_3CHO	Acetaldehyde	3.7	0.16
17	30.03	CH_2O	Formaldehyde (100 % purity)	2.7	0.081
			Sum of all Organic Molecules =	2,773	171
			Sum of all Inorganic and Organic Solutes =	5,927	412

Notes:
Target pH of final humidity condensate ersatz: pH = 7.6 ± 0.1, TOC = 103 mg/L
* DMSD concentration is variable and linked to the sources and sinks (air revitalization system's removal rates) of volatile methyl siloxanes, as well as the ionizing radiation conditions. Median value of ISS returned samples used here.

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).[14] 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.[3]

A value of 2 L/CM-day was selected for the daily volumetric production rate of raw urine for PGH. For ground testing, the flushwater volume of 0.3 L/day (6 flushers/CM-day at 0.05 L/flush) of deionized water remains the same as the flushwater volumes on ISS. Due to the unique biological, chemical, and physical properties of human urine, real urine collected from donors is recommended for ground testing to simulate a PGH. The value of 2 L/CM-day of raw urine is equal to the simulated humidity condensate collection rate. As discussed in the introduction, depending on crew activities, metabolism, payloads and environmental conditions, the mass ratio of urine to crew latent can be less than or greater than one. So, simplifying both values to the same value of 2 L/CM-day enables simple adjustments to be made as more clearly defined mission scenarios are provided for the actual rates of humidity condensate and urine production.

2. Urine Water Quality

A number of publications have summarized the composition of urine.[9,15] 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 emissions (e.g., ammonia). If a urine ersatz must be used in the early stages of technology development, one option is to add a real urine spike, on the order of 1 mL per liter of urine ersatz to provide a realistic microbial loading to the ersatz. Although freshly collected urine is normally used in testing, "aged" urine with bacteria capable of producing *urease* enzyme provide a good worst-case challenge to simulate an older system to challenge any physical chemical processors and their associated microbial control scheme.

C. Hygiene Waste Water

A wide range of personal hygiene options and scenarios are presented in the BVAD. Early stages of the PGH are expected to have limited hygiene similar to ISS practices but expand to full hygiene with maturity and under water-rich scenarios. About 0.4 kilograms of water per person (0.4 kg/CM-day) is assumed for personal hygiene practices on ISS, which, for this paper is considered an example of a "water-poor" or "water-conserving" scenario.

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 (relative to ISS). 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.[16] Total hygiene water use was 7.25 kg/CM-day. This paper uses those same values for the four main hygiene waste streams listed in Table 3. 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. Kitchen activities and the washing of utensils and management of food wastes are not included in this paper but will be incorporated in the future.

Table 3 is based on volunteers simulating the PGH hygiene practices with the personal care products and assumed water volumes. The labor-intensive method provides some of the body oils, sweat, dermal bacteria of a real crew. A hygiene ersatz is an alternative to conducting hygiene activities.[9] The baseline hygiene ersatz is undergoing review and updates to be used when a real hygiene waste water cannot be produced. The baseline assumptions of the water quantities and composition of the hygiene waste stream are expected to undergo the most modifications as the PGH water budget is refined to meet pending mission requirements and launch mass constraints. For example, surfactant formulations will be modified as needed to match the downstream water processor requirements and the crew cleansing requirements.

D. Laundry Waste Water

A significant update on the volumes of water required for laundry is presented here. Working under a Space Act Agreement between NASA and Proctor and Gamble,[17] a detergent formulation was developed in tandem with optimization of the concept of operations (ConOps) of the washing machine cycles to minimize water use per laundry load. The water required to wash clothes and towels for a crew of 4 was reduced from a daily average of 15 L/day to 4.3 L/day, a reduction of about 70 %. This reduction in water use will require a low-mass, partial gravity laundry machine, which is yet to be developed and tested.

Table 3 Assumed Hygiene Water and Product Usage for Partial Gravity Habitat - Water-Rich Scenario

Activity →	**Oral Hygiene**	**Hand Wash**	**Shower**	**Shave**	**Total**
Product →	Toothpaste	Body Wash	Body Wash	Shaving Cream	
Events/CM-day	2	8	1	0.25	**11**
L-water/Event	0.1	0.125	6	0.05	**6**
g-product/Event	1	1.5	25	0.8	**28**
L-water/CM-day	0.2	1	6	0.0125	**7.2**
g-product/CM-day	2	12	25	0.2	**39**
L-water/4CM-day	0.8	4	24	0.05	**29**
g-product/4CM-day	8	48	100	0.8	**157**
g-product/L-water	10	12	4.2	16	**5.4**
L-water/4CM-month	24	120	720	1.5	**866**
kg-product/4CM-month	0.24	1.44	3	0.024	**5**
L-water/4CM-year	292	1,460	8,760	18	**10,530**
kg-product/4CM-year	2.9	17.5	36.5	0.3	**57**

In addition to water for hygiene practices, the water required for washing of clothes and towels is a potentially significant load to the water recovery system. In the case of a microgravity laundry machine for a Mars transit mission, the breakeven equivalent system mass (ESM) point for having a water-based laundry was on the order of 13 months for clothes (assumed laundered mass rate of about 0.2 kg-clothes/CM-day), which reduced to 11 months with towels and wipes.[18] Due to the relatively high equivalent system mass, ESM, of water-based laundry compared to hygiene water uses, non-aqueous cleaning of clothes is 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 solution that supports crew health and comfort subject to the specific mass and power constraints of the PGH.

The water quality of laundry waste water is dominated by the detergent constituents, including the surfactants, enzymes, polymers, and soils on the clothing and towels (sweat, salts, oils, bacteria, and skin cells). Many of these body soils partition from body surfaces between the hygiene waste stream and the laundry waste stream. In one extreme scenario clothes could be washed during hygiene activities. 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. Fecal Water

The mass of water in fecal matter (~75 % by total fecal mass) is approximately 170 grams per crew member per day (170 g-water/CM-day) based on the average value from two references,[1,6] This assumed value of fecal water represents about 3 to 4 % of total water emissions from the body and about 1.4 % of the overall water content in the PGH waste streams assumed in this paper (Table 4). The range and factors determining the water content and composition of water in fecal matter in microgravity is not well quantified and could be elevated by microgravity[8] and physical activity by crew.[5] The HIHD[1] uses a conservatively high design value of 300 grams of fecal matter per crew member day, which corresponds to about 225 g-water/CM-day (assuming 75 % water mass fraction of total fecal mass). For the baseline values of this paper, the relative ratios of water masses (kilograms/CM-day) in crew latent (perspiration + respiration), urine, and feces are: 2 : 2 : 0.2 (WTR = 4.2 kg/CM-day). Exact values can be adjusted as more accurate estimates of body water flow rates become available for the PGH conditions of a given mission.

Current fecal matter collection on ISS does not currently provide direct water recovery. Both physical-chemical and biologically based technologies are under development to recover both water and nutrients from fecal matter and urine in missions beyond ISS. Another advantage of fecal water recovery and treatment is the stabilization and minimization of organic solid waste traditionally contributing to the solid waste load of the habitat.

F. Summary of Waste Streams

Table 4 summarizes the expected nominal daily mass flows of waste water per day for a PGH "water-rich" scenario, representing the values for testing of PGH water recovery technologies. The PGH waste stream scenario would generate a total of 12.7 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 manage and treat 50.8 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 in the PGH relative to the ISS baseline. For 30 days of operation with a crew of four, the PGH-WRS would receive a total influent of 1,510 kg of waste water (excluding 20 kg of fecal water) compared to 516 kg for a crew of 4 in the US segment on ISS. Figure 1 shows the water savings of the new optimized laundry ConOps that reduced laundry water by 70 % relative to previous baseline values. A similar optimization of hygiene practice ConOps is expected in order to reduce the large water demand of the hygiene stream (~57 % of total water in all waste streams). Figure 2 shows the waste stream cumulative water masses graphically for a PGH during a 30-day mission relative to ISS waste streams.

Table 4 Summary of PGH Waste Streams and Water Volumes for Ground Testing

PGH Waste Stream	L-water/ CM-day	Crew of 4: L-water/day	Crew of 4: L-water/month	% of Total
Hygiene	7.21	28.8	865	57%
Flushed Urine	2.30	9.2	276	18%
Humidity Condensate	2.00	8.0	240	16%
Laundry	1.07	4.3	129	8%
Fecal Water	0.17	0.68	20.4	1%
Total	**12.75**	**51.0**	**1,530**	**100%**

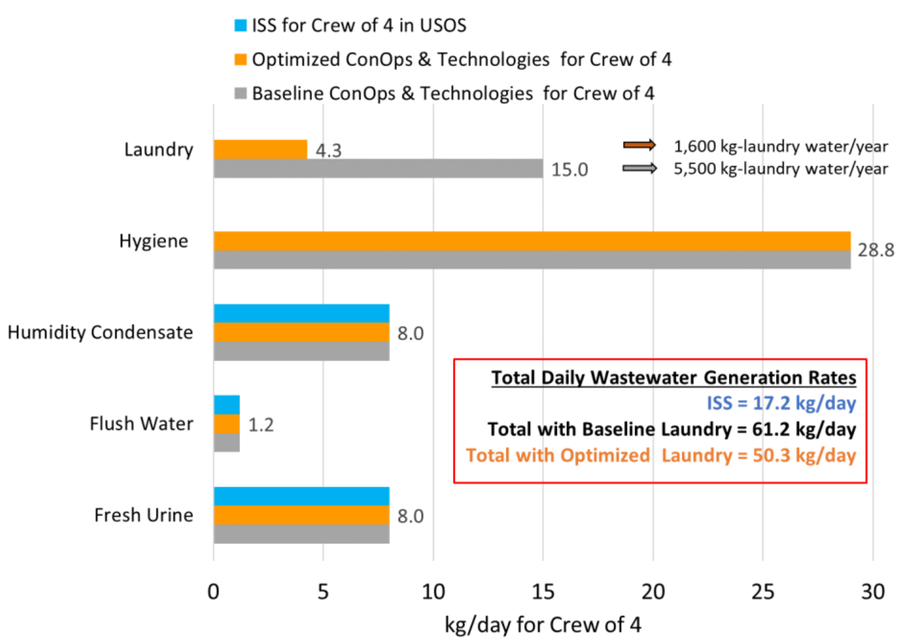

Figure 1 Updated Waste Stream Generation Rates with Optimized Laundry ConOps, Crew of 4, 30-days

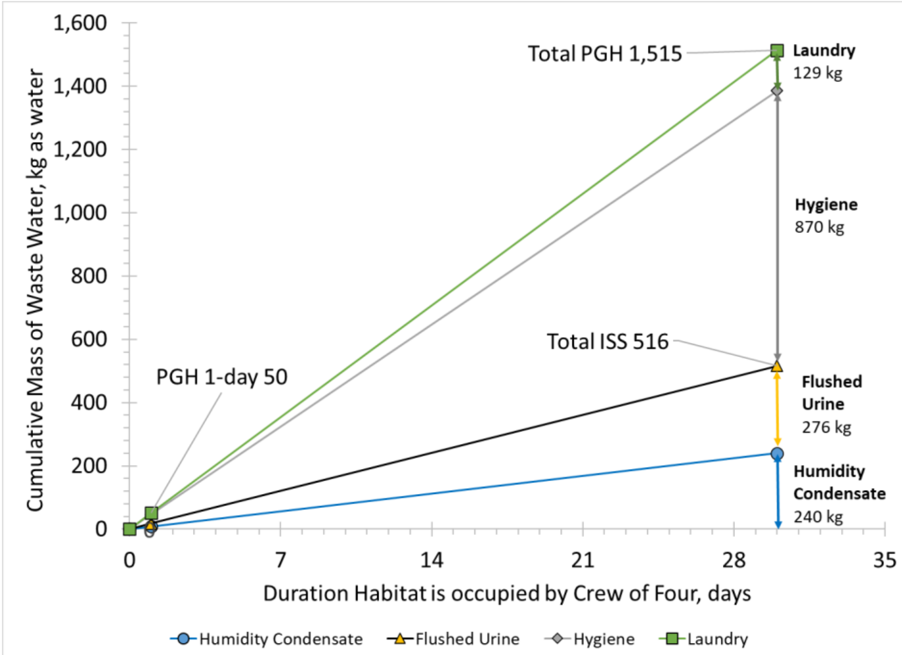

Figure 2 Cumulative Mass of Waste Streams for 30-Days, Crew of 4

III. 30-day Occupancy Durations

As pending details of lunar surface mission durations and their water-related activities and habitat "water budgets" are finalized, one interesting difference between the water recovery experience on ISS and other MGHs and the early lunar surface habitat emerges. Unlike ISS, which operates the water recovery system continuously, the PGH-WRS is expected to operate initially for 30 to 33 days and then be in a state of dormancy for 11 months.[18] A value of 30 days is used in this paper for calculations. The breakeven point for WRS equivalent system mass is typically on the order of several months or a year. For example, the breakeven point for a water-based laundry of clothes and towels for a Mars Transit Mission has been estimated to be 11 months. Therefore, the current approach is to consider the cumulative launch mass of return missions year after year. So, a clothes and towel reuse-enabling laundry and its water recovery mass savings would start to pay back in terms of ESM after 11 total mission trips of 30 day-duration occurring over a 10-year period. Designing for the recurring 30-day timeframe does have the potential to change the types of technologies that are down selected and optimized for the 30-day mission, with an advantage to systems, such as lightweight membranes that might have an operational lifetime on the order of slightly greater than 30 days. Technologies that have advantages under continuously occupied timeframes longer than 30 days, such as regenerative systems with natural biological processes utilizing plants and microbes that eliminate many of the current issues on ISS, such as odors and gas emissions from pretreated urine brines, problematic small organic compounds in air and water phases, and biofilm growth in waste water during transport and storage remain an active area of research. These differences in annually recurring, short-term versus long-term mission duration requirements and associated dormancy scenarios will affect the optimal management of water and selection of water recovery technologies in the partial gravity habitat.

IV. Summary

An evaluation and summary of the quantities and compositions of the four main types of waste streams expected 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 relative to ISS, full hygiene and laundry, were quantified and are continuing to be updated. The quantities reflect updated water volumes for laundry due to an optimization in the detergent-machine cycle concept of operations dependent on development of a partial gravity washing machine. The flow rates and ersatz formulations described here are intended to be used by technology developers to simulate a partial gravity habitat with humidity condensate, urine, full hygiene, and laundry. Fecal water quantities are estimated here but are not included in the current WRS system at this early stage. New analytical and experimental frameworks are being developed for optimizing the transition of continuously operated ISS-MGH heritage water recovery technologies (with quantified failure rates, operational performance, habitat integration optimization, consumables, mass, power, crew time) to an optimal combination of heritage and new technologies optimized for the PGH 30-day durations with long periods of dormancy. A similar transition process will be required in extending occupied durations to longer than 30 days. Continuous, day-to-day ground testing with simulated PGH waste water streams will provide water quantity and quality data on treatment system performance, power, mass, reliability, operational lifetime, and sizing data of technologies for trade studies to define the most promising technical processes, concepts of operations, and configurations of architectures for a partial gravity habitat under both short-term (≤ 30-day) and long-term (> 30-day) occupied scenarios.

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