Modeling Evolvable Water Recovery Systems for Short and Long-Duration Missions in Partial Gravity

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Water recovery technologies on the International Space Station (ISS) are designed and optimized for microgravity environments, thus creating a need for innovative systems optimized for mission operations in the presence of gravity. Alternative water recovery technologies under research by the Life Support Systems division were compiled into a series of Partial Gravity Water Recovery System (PGWRS) architectures. Individual unit processes were modeled via fundamental physical-chemical process equations to simulate their method of treatment, including chemical or biological oxidation, flash evaporation, filtration, or adsorption and ion exchange. Dimension and sizing data were then utilized to scale each architecture. Modeling was completed on an assortment of architectures assuming three scenarios in which treatment methods could take advantage of partial gravity: a short-duration mission with a temporary surface habitat, a longer duration mission with a more permanent habitat, and a long duration mission with minimal resupply. Total system mass was estimated to quantitatively compare architectures within scenarios, but qualitative observations were also made regarding system robustness, flexibility, and capacity to meet more stringent demands. Technologies that traded most favorably between the scenarios were those that included a pre-oxidation stage to minimize mass loading to downstream absorption and ion exchange beds, exploited gravity in liquid-vapor separation processes, and reconstituted wastewater components into recyclable material streams.

Nomenclature

AES = Advanced Exploration Systems
AOP = Advanced Oxidative Process
BPA = Brine Processor Assembly
COD = Chemical Oxygen Demand
DA = Distillation Assembly
DMSD = Dimethylsilanediol
ECLSS = Environmental Control and Life Support Systems
EO = Electro Oxidation
EOME = Electro Oxidation Membrane Evaporator
ESM = Equivalent System Mass
GMABR = Greywater Membrane Biofilm Reactor
HC = Humidity Condensate
ISS = International Space Station
MABR = Membrane Aerated Biofilm Reactor
mt = metric ton (1000 kg)
OP = Operations – Moon to Mars Objectives
PGWRS = Partial Gravity Water Recovery System
PUP = Planetary Urine Processor
RO = Reverse Osmosis
SWEG = Spacecraft Water Exposure Guidelines
SAMBR = Suspended Aerobic Membrane Bioreactor
TH = Transportation & Habitation – Moon to Mars Objectives
TN = Total Nitrogen
TOC = Total Organic Carbon
TRL = Technology Readiness Level
UMABR = Urine Membrane Biofilm Reactor
UPA = Urine Processor Assembly
WHC = Waste & Hygiene Compartment
WPA = Water Processor Assembly
WRS = Water Recovery System

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I. Introduction

NASA released the Moon To Mars Architecture concept review in 2023[1], which justified the purpose behind returning to the Moon and identified key systems that should be advanced in upcoming years to ensure long-duration human habitation on the Lunar and Martian surfaces. Their stated philosophy involves "architecting from the right", a method to weigh the technological priorities supporting logistics, exploration, and sustained living of crew in space. However, if human presence is the stated goal, we must re-envision the environmental control and life support systems (ECLSS) that will comprise the deployed Lunar and Martian infrastructure. Partial Gravity Water Recovery Systems (PGWRS) are a suite of tools that have been investigated as potential candidates to add to the Moon to Mars Architecture portfolio[2].

The current methods employed to treat wastewater on the International Space Station (ISS)—e.g., distillation, filtration, and oxidation—have demonstrated successful sustained performance in microgravity[3]. Despite the availability to leverage full or partial gravity in a vastly different environment, however, the same baseline ISS architecture is currently projected as the primary architecture supporting Lunar and Martian missions[4]. The unit processes aboard the ISS benefit from their proximity in low Earth orbit and are skillfully managed despite existing issues with high expendable usage, high temperature and pressure components, and hazardous pretreatment chemicals[3,5]. Widening the distance between crew operation and Earth without addressing the underlying issues could jeopardize the completion of operations (OP) and habitation (TH) goals expressed in the Moon to Mars Objective. Considering past estimates of manned missions lasting 30 months would require over 2,200 kg of water and treatment of nearly 5,700 kg of waste[6], there exists a need for innovative solutions in the ECLSS domain within the near-term and long-term future.

The summary below describes the current PGWRS modeling framework detailing how and where evolvable treatment architectures could fit into the Artemis and Martian mission roadmap.

- **Short-Term Relevance:** the PGWRS modeling design framework gives us flexibility to anticipate realistic scenarios NASA could face as it prepares to land crew on the Lunar surface. We use an evolvable approach to project performance of relatively low TRL technologies currently being researched to supplement portions of the baseline water treatment architecture.
- **Medium-Term Relevance:** modeling efforts evolved to include the capture and recovery of material contained within wastewater water as a regenerative *in situ* treatment technique.
- **Long-Term Relevance:** models forecast the advanced unit processes/architectures capable of high recovery thresholds (using membranes or liquid-gas separation), but with additional focus on sustained recovery of water, energy, and nutrients without resupply (i.e., closed loop)

This analysis examines the trade between several PGWRS architectures and the current ISS treatment architecture, and provides initial guidance (pending integrated testing) on what situations in the short and long term could benefit from the implementation of alternative PGWRS technologies.

II. Summary of Water Recovery Technologies

A. ISS Water Recovery Architecture

The baseline water recovery system (WRS) includes a set of treatment unit processes that service the urine stream from the waste & hygiene compartment (WHC)[3]. The WRS must pretreat the urine to prevent precipitation of minerals in the downstream distillation assembly (DA) of the urine processor assembly (UPA), and provide residual disinfection to control microbial growth within the lines[7]. The DA evaporates water from solution via centrifugation at low pressure, and the resulting water vapor is condensed and collected. The brine solution left after water evaporation in the DA is sent to a brine processor assembly (BPA)—a recently installed technology that improved the water recovery from 85% in 2016 (after implementing urine pretreatment) to over 95%[8]. Successful integration and operation of the BPA exemplifies the added value that can materialize when alternative solutions are applied to baseline architecture. If a relatively new technology like brine processing can coalesce with the existing WRS in microgravity to recover critical resources, further modifications can be made in the future to address specific treatment needs in partial gravity environments.

The Water Processor Assembly (WPA) is a subsequent leg of the WRS that handles the bulk of the mixed wastewater loads aboard the ISS; any distillate that was condensed in the UPA is sent to the WPA along with collected humidity condensate (HC), and any water produced from the CO_2 Reduction System (Sabatier reactor)[3]. A detailed

summary of the various wastewater chemical compositions can be found in the Baryakova & Lange (2020), but generally speaking, the wide array of wastewater types and loads can pose a challenge for treatment systems that are not designed for flexibility. The WPA currently processes relatively dilute, low conductivity wastewater through a series of filters that incrementally decrease in pore size, followed by adsorbent and ion exchange multifiltration to remove dissolved organic and inorganic material, respectively. Recalcitrant or volatile organic matter and any bacteria are oxidized in a catalytic reactor with applied heat and pressure before final removal of reactor byproducts via another ion exchange bed[3].

Historically, the ISS WRS has handled increasing loads and met performance criteria, although subsystem managers have had to navigate occasional failure events. One existing issue in the WPA involving an unremoved contaminant, dimethylsilanediol (DMSD), has affected operation and caused early replacement of filtration components[3,9]. The catalytic reactor has documented failures caused by leaks that limit the use life to a couple of years. Furthermore, the various filtration beds within the WPA have an outsized expendable usage rate, mainly because bed capacity is dictated by dissolved solids breakthrough and observed conductivity spikes[10]. Finally, microbial stabilization of wastewater other than urine is not addressed in the ISS WRS architecture. According to Moon to Mars objectives, infrastructure enabling sustained human presence should minimize consumable material, reduce potential risks, and be robust enough to handle prolonged dormancy. These challenges prompted us to examine what tradeoffs exist between the ISS baseline and other recovery technologies under various scenarios experienced in partial gravity environments.

B. Partial Gravity Water Recovery System Technologies

Past PGWRS analysis details the general philosophy in establishing a process flow schematic and in setting up the portfolio of candidate technologies considered in the trade[2]. The architecture was separated into stages to examine what benefits could be gained by the application of advanced treatment technologies on particular wastewater streams, characterized by past experimental data[11-13]. The majority of wastewater chemical constituents originate from the urine stream, as mentioned previously, and particular focus is paid to recovering the water from this liquid stream. However, sustained human activities during Lunar and Martian missions demand increased treatment capacity, so additional to urine, we considered humidity condensate, and wash/hygiene wastewater in evolving PGWRS architecture models.

Table 1 briefly summarizes the full list of PGWRS technologies included in the trade study. Many of the technologies are low technology readiness level (TRL), between 3 and 5. It was the goal of this study to incorporate empirical observations and real performance data to produce higher fidelity models, facilitating the advance of designs to higher TRLs. Advanced oxidative processes (AOPs) in Table 1 typically provide oxidizing power in the form of free radicals—highly reactive intermediate species that react quickly with organic matter. Urine treatment processes are focused on stabilizing the nitrogenous constituents in urine, inhibiting the oxidation of urea to its unwanted product, ammonia gas. The urine processing methods ranged from physical-chemical to biological. Other advanced biological technologies designed to treat wastewaters containing carbon (greywater or hygiene water) are included in various scenarios in the short and long-term.

Table 1. PGWRS Candidate Technologies

Technology Name	Description	Source
Advanced Oxidation Processes		
Ultraviolet/Hydrogen Peroxide (UV/H_2O_2)	H_2O_2 reaction with UV light forms OH· radicals, a highly reactive species that oxidizes organic matter and stabilizes wastewater	14, 15
Electrooxidation (EO)	Formation of oxidizing species such as free chlorine from an electrolyte via electron transfer between anode and cathode	16
Urine Processing		
Planetary Urine Processor (PUP)	Vacuum distillation and heat cause a phase change, and water evaporates from urine, leaving behind a dense precipitate inorganic brine	17
Electrooxidation/Membrane Evaporator (EOME)	Formation of oxidizing species such as free chlorine from an electrolyte via electron transfer between anode and cathode, followed by heated gas-liquid contact for evaporation and brine recovery	16

Table 1 (continued)

Urine Membrane Aerobic Biofilm Reactor (UMABR)	Microbial organisms process the carbon and organic nitrogen in urine and flush water within a tank with specialized oxygen-permeable membranes	[18]
Biological Wastewater Processing		
Greywater Aerobic Membrane Biofilm Reactor (GMABR)	Microbial organisms process the organic matter in grey wastewater with additional downstream reverse osmosis (RO) unit for solids handling	[19, 20]
Suspended Aerobic Membrane Bioreactor (SAMBR)	Common microbial bacteria groups perform nitrogen removal under conditions ions of a designed environment and size-exclusionary membrane filtration	[21]

III. Early Artemis PGWRS Solutions: Light-Weight Treatment Concept

A. Environmental Control and Life Support Allocation

Establishing a Lunar surface habitat (SH) is a key milestone for the Artemis missions and in NASA's Moon to Mars strategy. The infrastructure requirements must include equipment to service at least four crew members for a duration of 30 days[4]. The Spacecraft Water Exposure Guidelines (SWEG) specify limits on total organic carbon (TOC) and ammonia to <3 mg/L and <1 mg/L, respectively[22]. Total nitrogen (TN) limits are not listed in in the SWEG, although the Environmental Protection Agency advises a range of 2-6 mg/L[23]. Along with treatment quality, multiple missions will be non-contiguous, and any infrastructure left behind must be robust enough to survive dormant conditions. Moreover, logistics and operations of the mission undertaking is expected to experience severe ECLSS limitations—a maximum allotment of 2 mt per surface lander. Initial estimates concluded that an "open loop" strategy, where all material is launched, used, and disposed, will exceed the required ECLSS threshold[4]. Their results asserted that reaching the target ECLSS allotment can only be achieved with upfront recovery process capacity (oxygen regeneration, water recovery, urine, and brine processing), although there exists a possibility for more stringent restrictions as plans for the surface habitat evolve.

We developed a light-weight treatment concept architecture for these early scenarios with ECLSS limits that could trade well as a standalone water recovery unit process, but more realistically, could be integrated with existing baseline ISS technologies. Because of the difference in constituent components and the success the UPA and BPA have had handling urine, the focus of this initial assessment was conducted piecewise starting with HC—a dilute wastewater stream containing <500 mg/L TOC and <100 mg/L TN that is currently treated via oxidation in the catalytic reactor. PGWRS technologies were traded against a scaled-down WPA (the ISS baseline treatment process) using equivalent system mass (ESM), ignoring urine processing for this scenario and assuming only HC.

B. PGWRS Light Weight Technologies

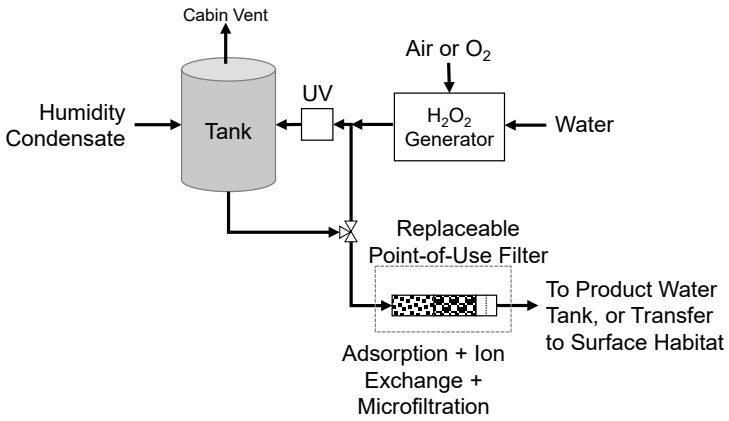


Figure 1. UV/H_2O_2 Light Weight Design. *Low concentration of H_2O_2 and stored water goes to UV cell for $OH\cdot$ formation. Disinfection residual is expected in a small storage tank.*

According to Verostko et al., the main sources of TOC in the HC waste stream come from ethanol, acetate, and propanediol, with nitrogen mainly in the form of ammonium (NH_4^+)[12]. It is also widely observed that these chemical compounds react readily with intermediate species, such as hydroxyl radicals ($OH\cdot$) or free chlorine (Cl_2, HOCl, ClO^-)[16,24], based on pseudo-first order reaction rate constants. Both of these oxidative chemical species can simultaneously provide disinfection properties to stabilize stored treated water. One part of the light-weight design concept centers around technologies that generate these two types of reactive species to effectively treat contaminants in HC with minimal mass, power, and volume (see

Figures 1 and 2). The UV/H_2O_2 and EO processes, part of a broader category of advanced oxidation processes (AOPs), are currently low TRL and require more testing to validate their use in the field, but their modeling here provides valuable insight into the potential trade compared directly with a scaled ISS baseline architecture.

A more passive approach utilizes biology to perform chemical oxidation to break down the organic components in the HC wastewater stream. The greywater membrane aerated biofilm reactor (GMABR) is a PGWRS candidate technology in which bacteria proliferate on the surface of a membrane by metabolizing organic carbon and nitrogen with a small input of oxygen. Experimental results have shown that the GMABR could effectively handle a dilute wastewater[20], but moreover, the system has demonstrated ability to enter a deep hibernation[25] as an answer to potential dormancy questions. The GMABR process was modestly scaled down according to the HC flow in this scenario and included in the overall trade with the chemical oxidation processes above and the ISS baseline architecture.

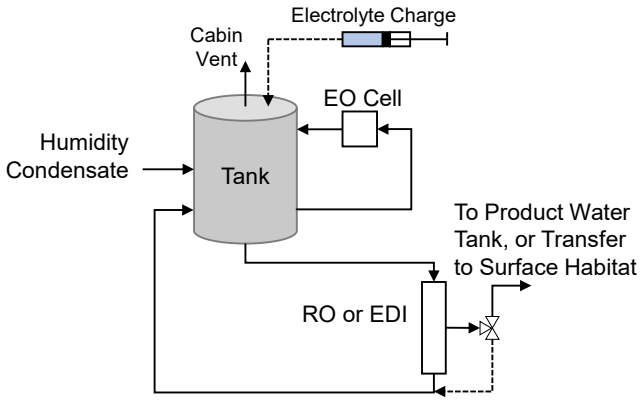


Figure 2. EO Light Weight Design. *Low concentration of sodium electrolyte and stored water goes to EO cell for FC formation. Disinfection residual is expected in a small storage tank.*

C. Results

The first step was to simulate the light-weight concept performance in Aspen Custom Modeler; the system and component mass balance was solved using fundamental unit process equations, reaction kinetics, and/or stoichiometry. The modeled flow streams were then transferred to a sizing spreadsheet, where the specific dimensions of each unit process were provided to estimate ESM. The results for a 30-day mission with four crew are shown in Figure 3. It is clear that any type of regenerative ECLSS infrastructure is going to trade far better than an open loop strategy, in which the commensurate metabolic water and sweat expelled by the crew is supplied in launch mass. This observation aligns with the results of Howard et al. (2022). Between the light-weight concepts and the ISS baseline architecture modeled in this scenario, the partial gravity AOP system mass estimates suggest advantages in upfront and resupply weight over an optimized WPA employed in microgravity on the ISS. Modest differences in system volume and power demand were seen between the individual treatment systems, but this had no real effect on total ESM. It should be noted this modeling effort assumed the WPA can be scaled down by decreasing the dimensions of key equipment and eliminating unused portions of the multifiltration beds to treat a single HC flow stream.

Modeling different variations of the two AOP technologies led to the most favorable system mass, but also revealed insights into appropriate ways of operating the treatment units. Two columns are shown in Figure 2 listing UV/H_2O_2 and UV-C/ H_2O_2, signifying the type of bulb used in each UV flow cell. The former is a standard mercury bulb with high wattage output; the latter was a configuration of three UV-C LED bulbs with lower wattage and lower efficiency operated in parallel. The standard UV bulb has a modest advantage in mass over UV-C LED, but is inherently riskier from a health and safety perspective due to its content of mercury[15]. The volume of H_2O_2 used in this system is so small (<1 L) that further reductions could be achieved to LED bulbs by simply eliminating the generator and supplying the required chemical oxidant for the mission duration. Similarly, it was found through modeling that the EO system greatly benefitted from the addition of a reverse osmosis (RO) unit before final polishing. Although the unit does require more upmass, the RO unit allows the system to be almost completely regenerative, i.e., it consumes and expends next to no material and recaptures ions for oxidizing power in the EO.

At first, it would seem the biological option does not trade as favorably in this scenario; however, this analysis was performed on a single 30-day mission. The GMABR installation is the largest contributor to the overall system mass, but it serves as a replacement in the system design for any installed tankage and has lower consumables and expendables than the baseline. In the next section, we investigate different wastewater loads that take advantage of the extra capacity provided by the GMABR. Future research could investigate either modifying the GMABR to fit a light-weight design or employing other biological methods, such as a trickling filter, to remove organic material using minimal resources.

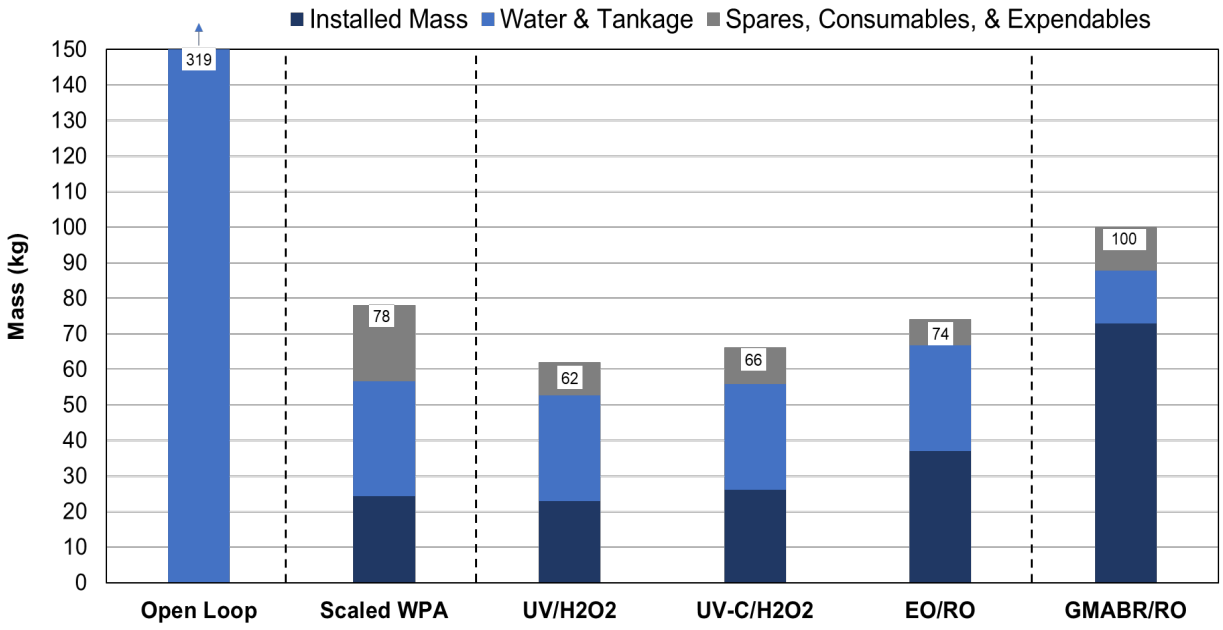


Figure 3: System mass requirements for Light Weight PGWRS compared to Open Loop and ISS WPA Design. *Consumables and expendables based on 30 days.*

IV. Evolvable PGWRS Architectures for Moon and Mars

A. Treatment and Recovery for Mature Lunar/Martian Habitats

The logistics and level of engineering design required for a completely self-sustaining habitat is formidable, and because of the complexity, any proposed innovation to the WRS status quo currently faces a headwind. Nevertheless, the fact remains that the current WRS architecture used aboard the ISS would require an insurmountable amount of resources to process the sheer volume of wastewater produced by crew members during a long duration mission[6]. Furthermore, the nexus of water and nutrient handling becomes more premium as *in situ* generation of fertilizers can promote plant production, offsetting the amount of packaged food needed to be launched. Some influent streams, such as the phosphoric acid pretreat solution, may become unnecessary with inclusion of PGWRS technologies, and micronutrients like phosphorus and nitrogen could instead be regarded as regenerative material.

In order to address the gaps in treatment, the current paradigm needs to shift towards a more holistic, closed-loop process design. In a similar manner as the previous methods, modeling was conducted on various configurations of PGWRS technologies, and the final ESM was compared against the ISS baseline architecture. Our analysis was performed using the full set of influent wastewater flows (including urine, humidity condensate, hygiene & laundry water) expected for a mature habit hosting four crew over 30 days. Past studies have shown hygiene and laundry water have a considerable effect on overall mass and volume reduction for packaged goods[26]. Inclusion of new greywater influent streams introduces significant differences to volume and mass loads to a treatment system, and therefore we will need to adapt water recovery architectures to service this need. The same treatment criteria as before were assumed in this design. To monitor the fate of nutrient flows, the concentration of chemical oxygen demand (COD), an approximation for all biodegradable and non-biodegradable carbon, as well as nitrogen (as TN), and phosphorus (PO_4 as P) were monitored throughout the system outputs. A Sankey diagram was then created using the calculated mass of these variables throughout their specific flow paths.

B. Results

The model scenarios evolved from the previous light weight concept to include higher wastewater loads anticipated for a future mature habitat on the Moon or Mars. As observed previously, the open loop strategy adds substantial mass to be supplied (over 1,800 kg per month), which once again reinforces the need for some allotted ECLSS/WRS. Implementing the ISS baseline architecture (WPA, UPA, BPA) does reduce this overall system mass, and the installed treatment mass tends to show value with higher imposed wastewater loading. However, PGWRS technologies (AOP

and biological) are shown to provide further overall mass reductions for multiple reasons, which can be analyzed sequentially from left to right columns in Figure 4. Within the first segmented lines, the urine processing remains unchanged from the current ISS architecture. Alternative processing of mixed greywater (hygiene and humidity condensate)—i.e., implementing a pre-oxidation stage utilizing the various intermediate species generated in either a UV flow cell or EO cell instead of the catalytic reactor—accounts for the difference in resupply water and consumables/expendables mass to close the recovery loop. The generation of oxidative intermediates provides chemical residual, therefore the treated water could either be sent to multifiltration for final polishing to become potable water or, as was modeled in this scenario, recycled back to urine processing as a stabilizing agent[17] and eliminating the pretreat influent stream. It is important to note that more laboratory testing is required particularly with these technologies to confirm reaction kinetics of a mixed greywater, but the resulting payoff of developing these systems could be avoidance of the serious challenges face by the catalytic reactor system.

Yet another strategy would be to implement biological-based designs, not only as a method for mass savings (as demonstrated in Figure 4), but because biologically stabilized wastewaters have utility in other parts of a habitat. As an example, effluent from a GMABR is not quality enough for human consumption, but could be used to water crops, or recycled as flush water, which reduces storage capacity and increases the efficiency of installed infrastructure. Installing a SAMBR module in a PGWRS architecture could allow for simultaneous biological removal with membrane filtration, allowing simultaneous treatment of the crew urine and fecal stream, which is currently not considered in any current architecture. Custom design of the various compartments within a biological treatment process could provide an environment for specialized microorganisms to oxidize ammonia and organic matter, generate nitrogen gas for cabin atmosphere revitalization, recapture phosphorus as a means for fertilizer production, emit energy-rich resources (such as methane gas), and more.

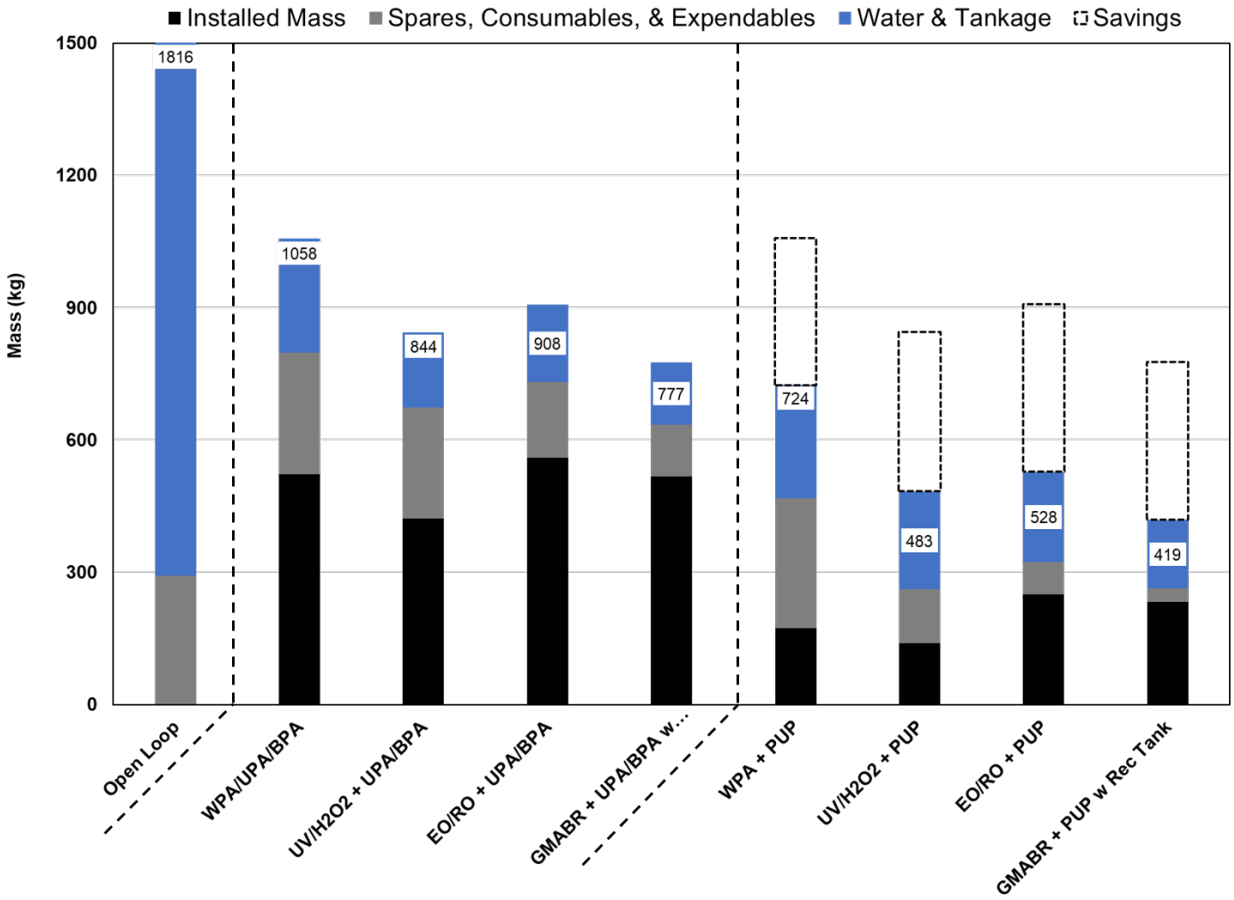


Figure 4: System mass requirements for Mature Habitat compared to Open Loop and ISS WPA Design. *Consumables and expendables based on 30 days.*

Demonstrated on the right half of Figure 4 are the resulting masses for systems that employ an alternative urine processor, the PUP, in lieu of the conventional UPA/BPA design. The Advanced Exploration Systems (AES) group holds PUP as one in a portfolio of next generation ECLSS technologies that is specifically designed to take advantage of gravity. In this case, the urine processing stage benefits from the ability to gravity-separate liquid and gas streams, combining two larger evaporation and precipitation steps into a single unit process. The experimental PUP and GMABR designs combined into a single system resulted in the lowest overall system mass, which is mainly attributable to their low reported expendable and consumable supplies. The use of EOME as an alternative technology in the urine processing stage was found to reduce architecture mass to a similar degree as the PUP. Super Critical Water Oxidation is another type of unit process that is under investigation through AES and could be a relevant tool in the PGWRS portfolio, but it does not yet have enough data generated for useful analysis in this case. Further tradeoffs between alternate urine processors need to be identified with specific quantitative and qualitative metrics and validated using experimental results.

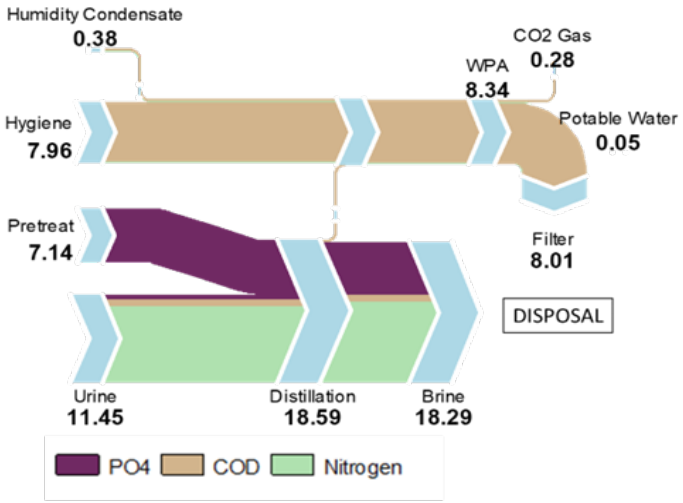


Figure 5. Fate of Nutrients within ISS treatment architecture. *Listed values in each flow stream are in units of mass (kg).*

Regardless of configuration or type of individual processing units, it is plausible from the model results to conclude that the current ECLSS mass limitations can be met (or even exceeded) using PGWRS. This does not necessarily require wholesale changes to the baseline architecture, although modifying the treatment strategy to implement PGWRS technologies does appear to have tradeoff value, and more model development concurrent with specific experiment procedures is recommended. Improving system modeling can also expand awareness on the fate of material other than water in a treatment system that could notably impact supply logistics.

A long-term vision of water recovery is inevitably linked with what is contained in a waste stream and what can be derived from the waste, most importantly: nutrients and energy. Manipulating water throughout a design is relatively straightforward; however, reassembling micronutrients back into a useful form or recapturing spent carbon from an absorption step is much more difficult and would require an inordinate amount of downstream processing resources to reclaim. The Sankey diagram in Figure 5 shows various nutrient flow streams, originating from their source influent and flowing throughout the treatment processes. It is immediately apparent that the current distillation and brine processes on the ISS create a direct throughline to disposal of phosphorus (purple) and nitrogen (green). The carbon (as COD, brown) contained within hygiene water is mostly removed via filtration, which again begs the question if the catalytic reactor is optimal from a system level design perspective. Intentional design for nutrient recovery and energy capture might involve the same PGWRS strategies mentioned previously—e.g., elimination of the urine pretreatment with a recycled H_2O_2 stream, pre-oxidation of carbon to CO_2 for water generation in the Sabatier reactor, and nitrogen removal via a biological reactor.

V. Conclusions

- PGWRS technologies are being developed and tested for Lunar or Martian missions that could provide benefits over the baseline treatment architecture currently employed aboard the ISS that was designed primarily for microgravity
- There are near-term scenarios where PGWRS light weight conceptual designs could supplement elements of the planned Lunar regenerative ECLSS water recovery architecture. The oxidative processes were anticipated to treat humidity condensate as a way of alleviating mass limitations imposed by the Lunar surface lander. Furthermore, such processes can provide microbial stabilization of stored wastewater that is not existent in the ISS WRS architecture. Future experimental verification of the concept in a laboratory environment is recommended.

- Various PGWRS architectures can be scaled to handle the wastewater loads expected to exist as off-world habitats move to a mature state. Utilizing gravity in the recovery process becomes more attractive as resource requirements escalate in longer duration missions. Stabilization of stored wastewater becomes critical as the influent wastewaters expand to include hygiene and laundry effluents with high microbial loads.
- An evolvable approach taken here factored in nutrients as part of the criteria determining success in fully closing the mass balance loop.

Acknowledgments

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