

Creating a Wastewater Technology ‘Toolbox’ for Space Exploration ECLSS

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Abstract

Life Support Systems (LSS) are essential for manned spaceflight; without them, humans would not survive. Upcoming long-duration missions demand robust environmental control LSS (ECLSS) due to their insulation and limited prospect for immediate resupply. As part of LSS, water purification systems will require high reliability, sustainability, and efficiency due to transport mass limitations, because routine water delivery will be very difficult and costly to resupply future habitats. This suggests a highly effective treatment method and reuse of *every* wastewater source. A variety of wastewater streams are generated by crew, and although not all are currently treated, habitat success will require each stream to be treated and utilized as a ‘resource’ rather than ‘waste’. These wastewater streams include human wastewater (urine, feces), food waste (plate waste, inedible plant biomass), humidity condensate, hygiene water (shower, oral, handwash), and laundry. Proven technologies are often relied upon due to long-term operations. For future, longer-term missions, this paradigm must shift to include technologies based on meeting mission requirements rather than sacrificing productivity in lieu of proven existing technology capabilities. Many physical, chemical, and biological water-processing technologies are proven and established for terrestrial applications. Herein, these technologies were collected into a ‘toolbox’ to perform possible functions towards effective water purification steps in reduced gravity. Selection criteria are dependent on approach (physical, chemical, or biological), complexity/components, terrestrial performance, and potential applicability to space life support. Utilization of this ‘toolbox’ approach provides a streamline methodology for technology development and down-selection into future architecture in direct response to the dynamic space life support requirements. Establishing the ‘toolbox’ also provides organized and efficient identification of the most appropriate technologies. From there, the technologies with the largest potential to be configured for mission requirements can be further developed and appropriately assessed. This presentation seeks to provide a comprehensive review of space life support water purification requirements and challenges, as well as to present a ‘toolbox’ methodology of available technologies to aid in the difficult process of selecting appropriate LSS water purification for short and long-term NASA mission architectures.

Background

NASA’s Artemis Program mission architecture establishes habitats on the Moon by 2028 [ref]. These long-term missions require robust ECLSS hardware to ensure crew safety. In addition to recovering water for long-term survival, habitat wastewater purification technologies must emphasize the recovery of additional elemental resources embedded in these waste streams (N, P, C, etc.) to minimize waste production and resupply. Otherwise, water, fertilizers, and chemicals will need to be resupplied frequently to maintain reliability of mission success. Although current ISS ECLSS technologies are proven reliable, these technologies require consumables that are not ideal for long-duration missions, do not treat every wastewater stream generated by future crew, and do not provide recovery of resources aside from water. Future ECLSS will require the investigation of supplemental and alternative technologies. The development of these technologies will expand a technology ‘toolbox’, providing a modular ECLSS architecture that can be customized in response to mission requirements and habitat needs.

Early Planetary Base

Various Early Planetary Base (EPB) scenarios were identified by the Agency to assess probable wastewater streams’ production and overall composition that will require treatment. [ref] The Agency anticipates habitation scenarios to evolve and expand in maturity, capability, and crew size over time. The corresponding ECLSS water purification hardware must grow to meet changing mission and habitat needs. Table 1 shows this EPB evolution from an early “survivability mode,” focused on simple treatment and removal, to the later “sustainability mode,” focused on complex treatment and resource recovery. As the scenarios evolve, additional waste streams are included, thereby increasing complexity. Current ISS systems only address wastewater streams planned EPB scenarios 1 and 2. This leaves a huge technology gap and need for the Agency to address if NASA expects to perform manned long duration missions. The concept of evolution will first employ ISS-proven technologies; the architecture will then expand to provide enhanced sustainability with the incorporation of biologically based technologies with more resource recoverability and reusability.

Table 1. EPB Evolution of Wastewater Sources

EPB-01	EPB-02	EPB-03	EPB-04	EPB-05	EPB-06
Urine HC	Urine HC Hygiene	Urine HC Hygiene Laundry	Urine HC Hygiene Laundry Small-scale Plant	Urine HC Hygiene Laundry Large-scale Plant	Urine HC Hygiene Laundry Large-scale Plant Fecal Foodwaste

During habitat maturation, incorporation of additional wastewater streams is expected to be added to the ECLSS system to treat more complex and additional volumes of wastewater. First missions to establish habitats will be high-risk and will focus on crew survival. In these early missions, streams included for water recovery will likely be limited to high water content, easily treated

wastewater streams such as humidity concentrate and hygiene water. Treatment of these wastewater streams will employ highly reliable systems, which will provide NASA a foundation of development for exploration. Urine, currently treated aboard ISS, has a high water content and requires more complex water treatment. In early EPB untreated wastewater streams will be collected for discarding. For ISS, plant matter is collected with solid waste, whereas fecal matter is collected in an aluminum storage tank. These biohazardous waste streams become prime sources for bacterial and fungal feeding grounds if stored improperly in addition to taking up valuable space and volume in a space habitat. As these waste stockpiles become larger during longer duration missions, later missions will require technologies capable of treating these higher strength wastewaters and larger volumes will be included to provide habitat expansion.

A variety of available treatment technologies could be used to effectively treat the incoming wastewater at different points within the EPB evolution; the key to long-term sustainability will be utilizing “fit-for-purpose” technologies to provide ideal water streams for overall ECLSS water needs. For example, targeted treatment of human wastewater (*i.e.*, urine and fecal waste), tailored according to end-use and leaving sanitized residual nutrient content for downstream plant fertilizer, results in efficient resource recovery within treatment architecture. These tailored product streams are designated by Class I-III. Class I is treated completely to potable water, Class II is sanitized but non-potable, while Class III is sanitized irrigation water containing nutrients (termed “fertigation”).

Wastewater Stream Analysis

Understanding the mission architecture’s waste streams helps define which technologies are most appropriate for implementation into the ECLSS as EPB grows. Basic human generated wastewater streams include metabolic wastes (urine and fecal), gray water (hygiene and laundry), and humidity condensate. Additional streams include process-generated waters (e.g. Sabatier and science experimental wastes) and high water content solid wastes (food and plant biomass). The determination of whether a waste stream is considered solid waste or liquid waste will most likely occur based on water content and/or mission requirements. Presently within NASA this determination has not been established. Terrestrially urine and feces are treated together in combined flow toilets with rinse water due to the desire to recover high water concentration within fecal matter. Terrestrially, most high water content food waste can be diluted with rinse water, minced within a garbage disposal, and processed as part of hygiene wastewater streams. Yet, these terrestrial methods may or may not trade well in future space habitats.

To effectively re-utilize all valuable elemental resources from each of the planetary base waste streams, it is important to first thoroughly assess each stream and the respective generation rates for recovery potential. NASA predicted these generation rates and corresponding waste stream composition³. Table 2 identifies water recovery potential for expected wastewater streams in a future colony on a per crewmember basis; first missions are suggested to bring a crew of four, with potential for future expansion to more crew.

Table 2. Wastewater streams and respective water content²

WW Stream	Percent Water (%)	Production (kg/CM-day)
Urine	97	1.8
Condensate	99	1.95
Hygiene	99	7.35
Laundry	99	15
Fecal	76	0.13
Food waste	35-95	Unknown

ECLSS Space Technology Constraints

Developing new technologies for spaceflight hardware requires unique constraints. Size and mass restrictions are driving factors for technology infusion considering space availability within flight vehicles and habitats is a premium. Reducing system mass and size makes a technology more competitive when selecting between possible trade studies. At \$10,000/lb,⁷ launching hardware to space is very expensive, and there is a limited volume and mass permitted each launch. In addition, high reliability and robustness are required for any ECLSS hardware to ensure crew safety. Technologies should operate reliably, with predictable failures well understood and accounted for. For example, replacement parts for predicted failures such as tubing or spent media will be accounted for and included in overall system mass for the lifetime of the mission. Cost, schedule, supply chain (certificate of conformance on flight hardware parts, part availability, time to produce), and safety are other constraints that drive stakeholder requirements. By understanding technology predictable constraints, overall risk to mission success and astronaut safety can be properly mitigated.

Wastewater Technology Tools for the ‘Toolbox’

A variety of available technologies, the ‘tools’, can achieve one or many of the nine identified treatment requirements in Figure 1. Water cycling can be performed both biologically and by physical-chemical means. Biologically based technologies, tend to operate more sustainably, requiring fewer consumable inputs and more closely mimicking the natural cycling that occurs within Earth’s environment.⁴ Physical-chemical and biologically based technologies both provide benefits to the unique space constraints. In general, physical-chemical processes are faster but tend to require consumable inputs (e.g., chemical reagents/catalysts). Understanding the various technologies and their respective capabilities and limitations helps to develop a technology ‘toolbox’ to select from when establishing mission architecture.

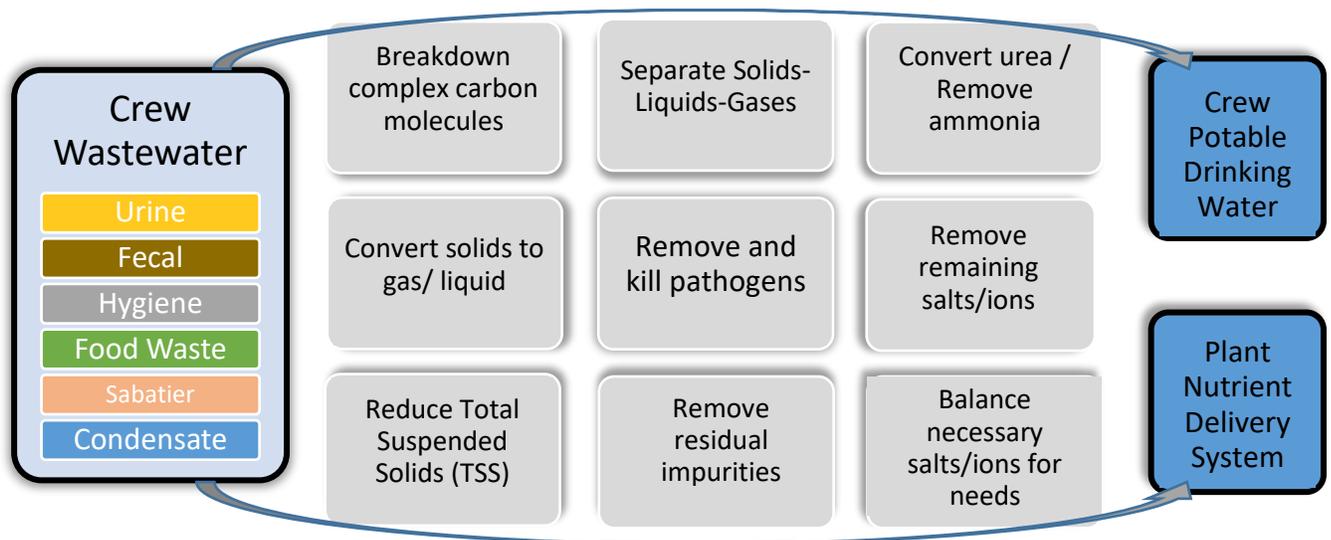


Figure 1. Functions necessary for wastewater purification.

Biological Treatment Processes

Biological treatment technologies couple existing biology with engineered hardware in order to mimic naturally occurring elemental cycling on Earth. These technologies have been well established terrestrially and are being investigated for their application for regenerative ECLSS. The biological nature of these technologies can primarily be categorized as aerobic, anaerobic, and photosynthetic.

Aerobic Bioreactors

Aerobic microorganisms require a constant input of oxygen and while producing carbon dioxide and large amounts of biomass during its rapid metabolic activities, making it ideal for low strength wastewater. Commercially aerobic microorganism are primarily utilized for low strength wastewater streams and take advantage of their ability to nitrify or convert ammonium, commonly found in urine, into nitrate which is more readily taken up by plants.⁵ Aerobic processes face challenges in for ECLSS applications primarily due to their commonly intensive energy requirement for aeration and the quick accumulation of inhibitory, excess biomass. While terrestrially a majority of excess biomass is often wasted, biochar technologies have been studied to recover energy and produce a byproduct that is suitable as a soil amendment.⁶

Anaerobic Bioreactors

Anaerobic treatment technologies are not as common as their aerobic counterparts in commercial municipal wastewater treatment primarily due to their relatively slower metabolism but are ideal for treating high strength blackwater such as fecal and food waste. Accordingly, these microorganisms do not produce nearly as much excess biomass, require no oxygen input, and produce an energy rich biogas for energy recovery. The inherent organic nutrients of the wastewater are continuously broken down in a digestive process, creating readily usable ions that are ideal for fertigation or can be further processed to create potable water.

Phototrophic Bioreactors

Phototrophic organisms are among a classification whose metabolism requirement is supplied by photosynthesis, a method of energy capture from light, primarily sunlight. Opposed to aerobic, phototrophic microorganisms intake carbon dioxide and produce oxygen. Terrestrially phototrophic microorganisms are used in wastewater treatment primarily for recovering nitrogen and phosphorus, post primary treatment process. They are also responsible for more than half of the oxygen produced globally, highlighting their importance to our terrestrial survival and could be so for surface habitats. Substantial research has been investigated into their potential use for dietary supplements, biosolids, and biofuel, which can be harvested from treatment cultures, dewatered, and further processed for such uses.

Physical-Chemical Treatment Processes

Physical-chemical processes are commonly coupled due to the nature of the processes. Physical-Chemical treatment systems utilize material and chemical properties to induce desired separation and conversion to treat wastewater and are often paired together to achieve these desired outcomes. These technologies makeup many of the core technologies first used in space exploration and are still the predominant technologies ECLSS.

Physical Treatment Processes

Physical treatment methods are used primarily to treat water utilizing the selective removal of constituents via methods such as physical retention, phase change, and ion capture. The primary methods for physical treatment include filtration, distillation, combustion, and sorption. Filtration is the physical selectivity and separation of desired components (i.e. particles, colloids, ions) with the use of a physical barrier. One of the most common forms of this physical barrier are membranes that contain pores of varying sizes to allow for the desired selective separation. While they provide instantaneous and reliable treatment they are subject to clogging from the build up of retentate known as fouling. This buildup of foulants commonly treated via chemical cleaning or the physical flow reversal, backwashing and can drastically increase the life of membranes. Distillation incurs thermodynamic changes to cause phase separation of water to vapor, to remove and recover the water from undesired constituents. A high degree of energy is typically needed to causes these thermodynamic changes and therefore is typically feasible only when a substantial source of energy is available and minimal treatment is required. Similarly, combustion exothermically oxidizes waste to volatize water and constituents and leave behind an ash or char which in some combustion treatments can be utilized as a soil amendment but in others can produce hazardous gasses and byproducts. Sorption uses a typically porous media with a high surface area to retain constituents in passing liquid and/or gasses. Most sorption media can be regenerated through various rejuvenation processes but cannot always be achieved in a space exploration scenario and are disposed of once spent.

Chemical Treatment Processes

Chemical water treatment is primarily used to neutralize, remove, or disinfect undesired constituents and microorganisms are often incorporated together as Advanced Oxidation Processes (AOP) for enhanced performance. AOPs can be combined with many different methods but primarily use a combination of ozone, peroxide, and ultraviolet (UV) radiation. Most AOPs utilize a source of consumable to achieve the desired degree of treatment and cannot always be

regenerated or generated *in situ* and in some cases such as hazardous by-products. However, compared with simple oxidation processes, AOPs completely neutralize a wide range of organics, constituents, and some pathogens at nominal conditions and can often be used on demand and as point of use treatment.

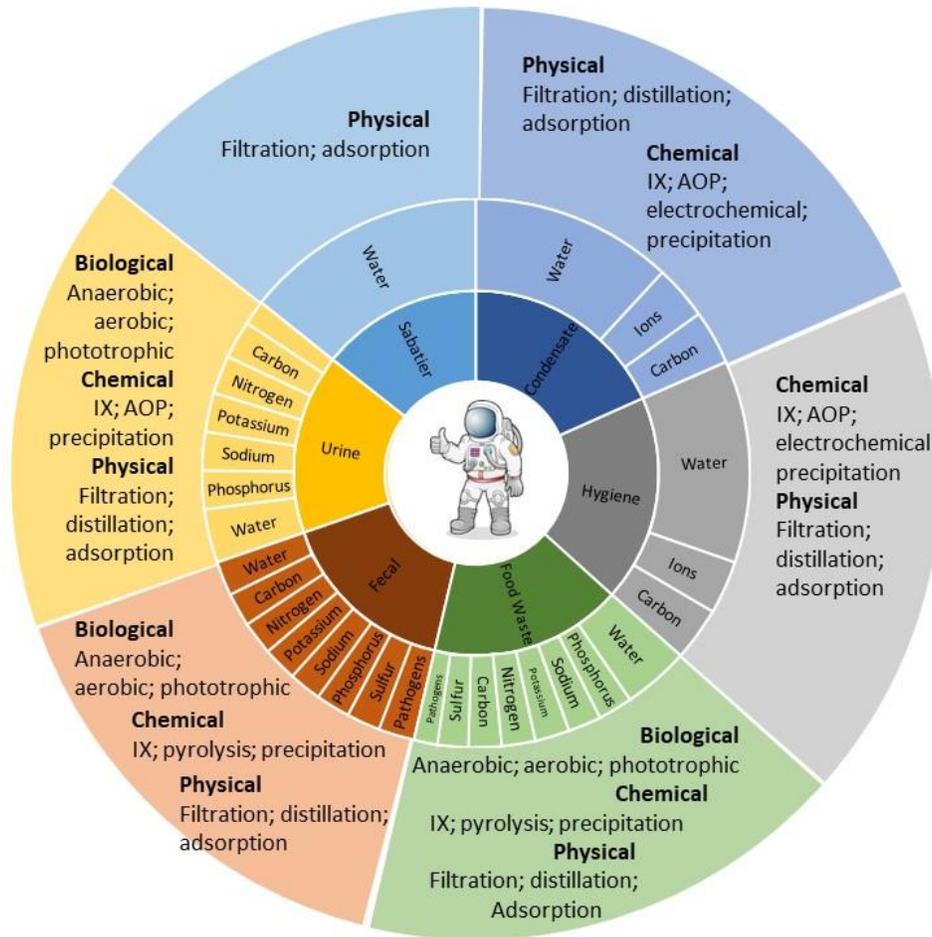


Figure 1. Crew-generated waste streams, recoverable resources, and appropriate treatment technologies. *Adapted from Pickett et al.*

Hybrid Treatment and Architectures

In order to overcome the unique challenges involved with providing sustainable water purification for long-duration space missions, an integrated, multi-stage technology design is likely. This future system architecture utilizes a combination of biological, physical-chemical, and hybrid processes to provide robustness and high reliability.

Hybrid Technology: Membrane Bioreactors

A membrane bioreactor is one example of a hybrid technology. Membrane bioreactors (MBRs) are a robust, proven system and have been successfully implemented in varying terrestrial

wastewater treatment applications¹⁷. Preceded by a bioreactor, conventionally of an aerobic or anaerobic nature, the effluent is fed to a permeable selective membrane that filters and rejects solid particulate material. In doing so a filtered permeate is produced that, depending on the filtration scale, is free of particulate solids, bacteria, viruses, colloids, dissolved salts, etc.¹⁷. Due to the fact that the membrane provides a barrier, virtually all biomass is retained and accumulates within the bioreactor, resulting a high biomass concentration. This high biomass concentration increases microbial activity and degradation which makes MBR's ideal for applications where mass and volume are critical metrics and have a smaller footprint than complementary systems¹⁸. Compared to conventional wastewater treatment systems, MBR's occupy approximately 75-80% less space and have the potential to be applied to lower scale environments¹⁸. Incorporating ultrafiltration membranes to the previously described bioreactors result in higher efficiency treatment, and lower mass and areal footprint systems for future surface habitat ECLSS.

Hybrid Architectures

Utilizing diverse, complementary treatment technologies, future habitat ECLSS can approach 'closed loop.' By 'closing the loop' on overall water purification, water losses will be minimal and resources will be recovered at every stage of the treatment process. For example, a shortcoming of current biological processes is start-up time. However, if couple with a complementary physical-chemical technology, more treatment burden can be placed on the physical-chemical system during the biological start-up period, with planned operations to shift treatment burden appropriately when the biological system is in nominal operating conditions. A similar scenario would occur if off-nominal conditions occurred, resulting in a biological system failure. With multiple, various treatment technologies in place, burden can shift during biological downtime. It is straightforward to account for backup filters, adsorbents, etc. for physical-chemical technology failures with quick mitigation procedure available to return to normal treatment operations. Hybrid architectures can provide more robust treatment with flexibility of stream treatment and flow diversion opportunity. In anomaly scenarios, water recovery for survival can be maintained with additional elemental recovery taking lower priority as needed.

Advantages to Overall ECLSS

In addition to clean potable water, the hybrid system architectures also produce various other useful outputs. Of course, the primary output of the overall system will be potable drinking water, produced at optimal efficiency. With biological treatment processes, partially treated wastewater streams can be utilized to provide substantial portions of nutrients for plant fertilization. It makes sense to combine the WP system architecture with a viable hydroponic plant system due to these excess plant fertilizers. Plant production requires 11 m² of growing area (for 50% dietary nutrient needs) as well as the bioreactors required to recover, carbon in particular, for high strength streams such as fecal and FW. The plants fed by these fertilizers will produce food resources for the crew in space. In addition to hydrogen gas, nitrogen gas, and plant fertilizers that the WP system produces, other outputs could include methane for use as energy to operate the system, carbon dioxide (CO₂) for plant growth, and oxygen for air revitalization.

Table 3. Closed-loop Ground Study Hybrid ECLSS Achievements

BLSS Closed-loop Achievements	Experiments
Complete water recovery with hybrid technologies	lunar palace 1 bios 3 biosphere 2 SCE
Complete air revitalization achieved from plants with integrated ECLSS	lunar palace 1 bios 3 biosphere 2 SCE
Some fertilizer produced from wastewater	bios 3
Some food production	SCE CEEF, biosphere 2 MELiSSA bios 3

Conclusion

Life support systems for future long duration missions will be heavily relied upon to keep crew alive during the most trying space exploration scenarios. Without regular resupply missions, ECLSS air and water revitalization hardware will be independently responsible for the long-term safety of crew. These technologies must simulate Earth’s environment efficiently, sustainably recycling valuable resources with high efficiency and low byproducts. Understanding the advantages and disadvantages of space applicable water purification technologies provides a ‘tool-box’ for habitat ECLSS architecture design. Based on mission needs and requirements, technology architectures can be customized accordingly. Future missions will focus on ECLSS architecture evolution to accommodate more colony habitants and achieve overall higher resiliency and robustness.