A Prototype Early Planetary Organic Processor Assembly (OPA) Based on Dual-Stage Anaerobic Membrane Bioreactor (AnMBR) for Fecal and Food Waste Treatment and Resource Recovery

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Long-duration, deep-space exploration and habitation missions demand robust and reliable technologies to ensure crew health, safety, and mission success. Local food production will be essential for crew nutrition and morale. However, at $10,000/lb, the payload costs and mass/volume limitations to transport and provide the necessary resources, including fertilizer, for an anticipated 30-month mission become challenging over time. For mission success and sustainability, the Environmental Control and Life Support System (ECLSS) of the near future will need to recover resources from all "waste" sources and be near-closed loop. Organic wastes (e.g., fecal and food) offer a renewable source of C, N, P, water and other trace elements necessary to sustain crop production. However, these high solid wastes are often difficult to treat due to factors including heterogeneity, complexity, high organic strength, and the presence of pathogens. To date, there is no flight-ready technology capable of treating mixed organic wastes, creating a technology gap for future space missions. To address this need, a prototype Organic Processor Assembly (OPA) was developed through collaboration between the University of South Florida (USF) and NASA's Kennedy Space Center (KSC). The OPA is based on the anaerobic membrane bioreactor (AnMBR), a hybrid technology coupling high-rate anaerobic digestion with membrane filtration. The system is designed for an early planetary base (EPB) scenario to aid in closing the resource recovery loop and decrease resupply dependence. This presentation discusses initial research pertaining to: 1) design challenges in maximizing hydraulic/organic throughput and Reliability, Availability, Maintainability, and Safety (RAMS) while minimizing mass and volume; 2) create capabilities for treating simulated high solids waste under steady and non-steady state conditions; and 3) measure solids performance parameter(s). Future research and development pertaining to further optimization on system operation, performance, and expanded treatment capabilities are presented.

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Nomenclature

AES	=	Advanced Exploration Systems
AnMBR	=	Anaerobic Membrane Bioreactor
BLSS	=	Bioregenerative Life Support System
C	=	Carbon
COD	=	Chemical Oxygen Demand
COPAS	=	Complex Organic Particulate Artificial Sewage
CRS	=	Cargo Resupply Mission
ECLSS	=	Environmental Control and Life Support Systems
EPB	=	Early Planetary Base
HEOMD	=	Human Exploration and Operations Mission Directorate
IRTD	=	Independent Research & Technology Development
ISS	=	International Space Station
KSC	=	Kennedy Space Center
N	=	Nitrogen, elemental
NASA	=	National Aeronautics and Space Agency
OPA	=	Organic Processor Assembly
P	=	Phosphorus
PFD	=	Process Flow Diagram
RAMS	=	Reliability, Availability, Maintainability, and Safety
TN	=	Total Nitrogen
TOC	=	Total Organic Carbon
TRL	=	Technology Readiness Level
TSS	=	Total Suspended Solids
USD	=	US Dollars
USF	=	University of South Florida
Veggie	=	Vegetable Production System
VSS	=	Volatile Suspended Solids
WRS	=	Water Recovery System
WPA	=	Water Processor Assembly

I. Introduction

THE Artemis program, which aims to land the first woman and first person of color on the Moon, marks another progressive step within the Space Age[2]. These missions will establish a long-term lunar presence, pioneer the way to Mars, and maintain long-duration space exploration and habitation[2]. This ambitious undertaking creates a new push for the research and development for innovative technologies to meet new programmatic requirements. The goal of achieving long-duration, deep-space human exploration presents NASA and its collaborators with some of the most trying technological challenges encountered since the Space Race. Many of these challenges stem from the harsh and dynamic environments encountered within space, on the Moon, and Mars. Current crewed space operations center primarily around the International Space Station, 220 miles above Earth, where support and resources are hours away and communication is instantaneous[3]. In comparison, a one way trip to the Moon is about three days, while the same for Mars is estimated to range from seven months to over a year and communication is expected to be delayed by approximately 20 minutes[4, 5]. With little to no resources readily available to support human life, artificial habitats for crew members in these environments will need to be robust, independent, and provide all the basic requirements to support life that is naturally granted on Earth, including the air we breathe and food we eat.

Environmental Control and Life Support System (ECLSS) technologies used aboard the International Space Station (ISS) are not optimized for long-duration, deep-space human exploration. As ECLSS technologies aboard the ISS are currently dependent on the regular resupply of consumables, continued use of such technologies in an extraplanetary habitat would likely result in significant financial, logistical, and operational burden. The same instantaneous communication, support, and resupply currently relied upon will no longer be a viable option. In the case of a 30-month mission, a single crew member will require 2250 kg of water, 1359 kg of food, and produce over 5678 kg of metabolic waste[1]. With a current payload cost of approximately 10,000 USD/lb (~4,535 USD/kg), the cost to provide the food and water for a single astronaut, during the 30-month mission, exceeds 16 million USD[6]. This shift to sustainable and regenerative technologies pertains to NASA's Technology Taxonomy, TX06.1, Environmental

Control and Life Support Systems and Habitation Systems and it's listed goal to: "maintain an environment suitable for sustaining human life throughout the duration of a mission."[7].

II. Background

The ability to long-term cultivate edible biomass is necessary for future ECLSS. The motivation for this development is driven by the aforementioned food requirements and associated costs to continuously transport supplies from Earth. The product of extensive research for edible crop production, the Vegetable Production System (Veggie) was developed at NASA's Kennedy Space Center[8]. Using controlled fertigation and nutrient application, this system is currently being tested aboard ISS to cultivate "pick and eat" crops as a food source testbed for long-duration space exploration and habitation[8]. However, the main source of calories and nutrients is delivered through cargo resupply (CRS) missions[8].

Organic wastes (fecal and food) are resources containing water, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, and many other elements necessary for plant growth. However, current ECLSS technologies aboard ISS only recycle low strength wastewater (condensate, hygiene, urine), not organic wastes. These high strength wastewaters are classified within NASA as solid wastes under the Logistics Reduction portfolio rather than wastewater which resides under Life Support and Habitation. The solid wastes are either discarded or subjected to thermal treatment. Most thermal processes (combustion, pyrolysis, gasification) cannot tolerate water content beyond 20-25%[9]. At the same time, existing water technologies are only intended to treat water with relatively low suspended solids. Yet, metabolic wastes usually do not present themselves in a convenient dichotomy of either wet or dry. For example, fecal and food waste are inherently high in water content and, when combined with rinse or flush water, become slurries or suspensions. Add in vomit and diarrhea, and it is clear that metabolic wastes exist across a spectrum of solids and water contents. Figures 1 and 2 summarizes ECLSS process streams and applicable technologies in an integrated fashion based on solids and water content. Enabling technologies that are agnostic to waste morphology, and robust enough to handle wet organic wastes ranging from solution to suspension to slurry are needed. However, such technologies are currently absent in the space ECLSS toolbox.

In an ideal future ECLSS architecture, technologies will comprehensively treat and recover resources in all wastewater streams, including fecal and food. To account for the expansion of the types of waste to be treated, treatment processes should utilize the best combinations of physical, chemical, and biological processes. The addition of these new technologies to existing ECLSS can create an architecture capable of processing diverse forms of waste for resource recovery. As part of the effort to work towards a comprehensive, integrated, and sustainable architecture, NASA and the University of South Florida collaborated to develop a treatment and resource recovery technology suitable for Early Planetary Base (EPB) scenarios. Termed the Organic Processor Assembly (OPA), this novel technology was designed, fabricated, and tested to create a valuable tool for bioregenerative water purification and resource recovery system architecture. The purpose of the OPA is to treat high-strength waste streams containing particulate organic matter, namely fecal and food wastes, that are not currently recovered by the ISS WRS.

At the heart of the OPA, is a hybrid biological-physical technology, coupling anaerobic digestion and membrane filtration, known as an anaerobic membrane bioreactor (AnMBR). The AnMBR breaks down complex organic waste fractions, such as fecal and food, that can be recovered for a myriad of applications, including fertilizer for plant production, and provide an absolute barrier to remove pathogens[10,11]. Anaerobic digestion, comprised of four sequential metabolic processes: hydrolysis, acetogenesis, acidogenesis, and methanogenesis that break down high-solid, complex organic waste and produces an energy rich biogas primarily composed of CH_4 and CO_2. The digested liquor passes through an ultrafiltration membrane filter for solid/liquid separation to produce a high-quality, nutrient-rich effluent which is pathogen free[12]. Downstream technologies can either utilize the effluent to support plant growth (fertigation) or further refine the effluent to potable water. The produced biogas can be used to offset the system's net energy requirement. General energy requirements of AnMBRs' range from 0.6-2.3 kWh/m^3 of treated effluent but can be as low as 0.4 kWh/m^3 [13].

The OPA technology is ideal for space applications, since it is able to handle high-strength wastewater and solids previously not processed for resource recovery. Table 1 provides an overview of inputs and outputs of the OPA. Beyond the waste stream, the OPA requires no additional inputs or consumables. Power needed for operation can be offset with the recovery of the produced biogas. The use of a pressure differential via pumps as the driving force behind the membrane flux is minimally impacted by gravitational forces. Consequently, the mass, volume, and energy footprints of the system are optimal for an EPB scenario.

		Constituents by type										Constituents by size		
Process Stream	Description	C	N	P	K	S	Na	Ca	Mg	Other ions	Pathogens	Particulate	Colloidal	Dissolved
Food Waste	High content of complex particulate OM, fibers, COD	4	3	3	2	3	2	2	2	2	2	4	4	3
Fecal	High content of complex particulate OM, fibers, COD, pathogens	4	3	3	2	3	2	2	2	2	4	4	4	3
Urine	Mod COD, organic N, urea, ammonium, phosphate, other salts	3	4	4	4	2	3	2	2	3	2	0	2	4
Hygiene	Low COD, constituents from skin and body secretions, environmental contaminants	2	2	1	1	1	2	1	1	2	2	2	2	3
Humidity	Mostly pure condensate, with contaminants from air and surfaces	1	1	0	1	0	1	0	0	1	1	0	0	2
Sabatier	Pure, potentially aggressive, can use for dilution, regeneration, backwash	0	0	0	0	0	0	0	0	1	1	0	0	0

Figure 1. ECLSS process streams and constituent breakdown. Notes: First two rows denote streams currently not addressed by technologies on ISS. Relative concentration: Very High (4) High (3), Medium (2), Low (1), Trace (0). COD = chemical oxygen demand[1].

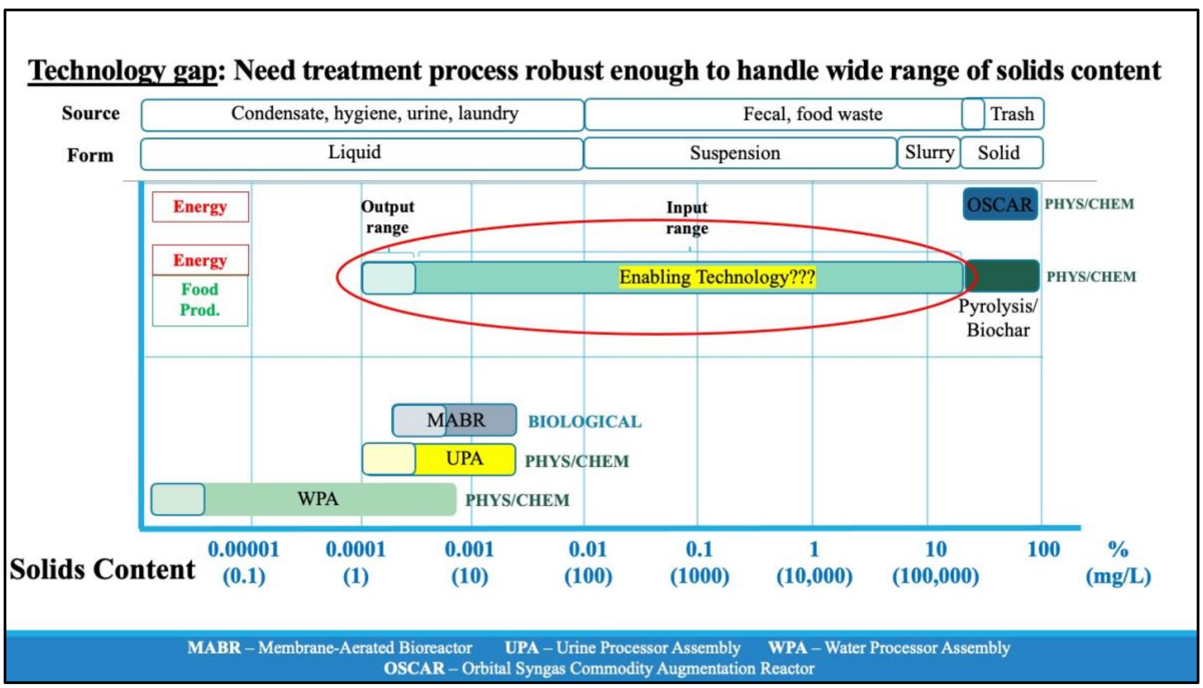


Figure 2. Applicable technologies based on solids content.

Table 1. OPA Products and Reuse Potential.

Input(s)	Output(s)			
	Products	**Primary Composition**	**Destination**	**Reuse Potential**
	Biomass	Organic carbon	Solid waste treatment	Biochar/compost
High strength wastewater (fecal and food waste) and Energy	Biogas	CH_4, CO_2	Collection	Energy and photosynthetic respiration
	Liquid effluent	Water with high nitrogen and phosphorous content	Downstream subsystems	Fertilizer and flush water

III. Design

Design challenges primarily stemmed from optimizing reactor geometry for optimal performance in reduced gravity and incorporating an automated control and monitoring scheme. The OPA's design was developed over several iterations to optimize its application and operation in varying space environments, including EPB scenarios. The system's housing was based on NASA's EXPRESS rack and designed to be compact, easily accessible, and modular for easy integration for possible flight demonstration[14]. For the allotted volume in an EXPRESS rack, rectangular reactor tanks were chosen as they were deemed to be the most optimal for utilization of the geometry and volume. The system was sized based on the solids content anticipated for the fecal and flush waste of a crew of four at a hydraulic throughput of approximately 2.5 L/d. The design of the AnMBR treatment process is comprised of a two-stage reactor that provides enhanced, stable wastewater treatment by optimizing two of the primary stages of anaerobic digestion: acidogenesis and methanogenesis[15]. The Stage 1 reactor is controlled to favorable conditions for acidogenesis, characterized by a slightly acidic environment, which rapidly breakdown the complex organic fractions of the blackwater waste. The Stage 2 reactor,

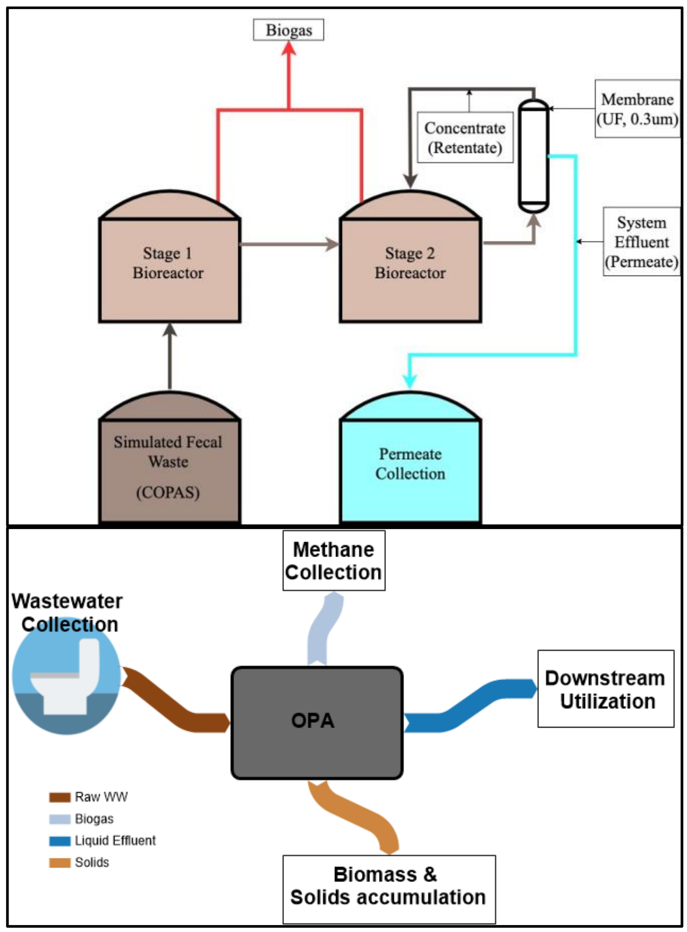


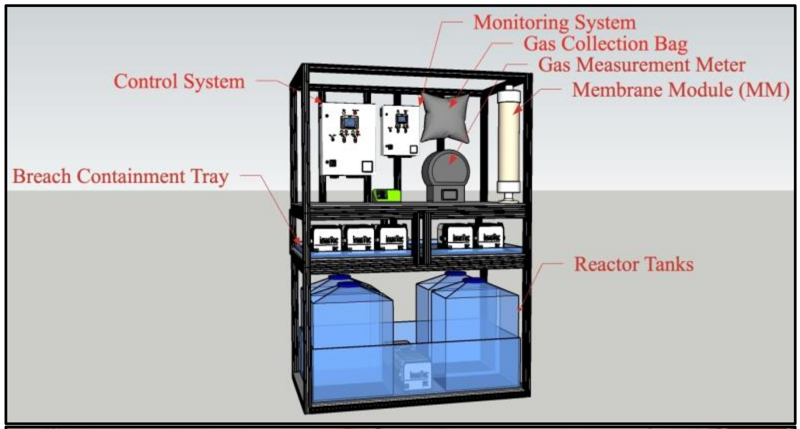
Figure 3. (top) OPA Process Flow Diagram (PFD), (bottom) OPA Architecture ECLSS Configuration.

characterized by a neutral pH environment, consumes the deconstructed organic fractions to produce biogas through methanogenesis. The Stage 2 effluent is filtered through an ultrafiltration membrane with a pore size of 0.03 um to create a high quality, pathogen-free, and nutrient-rich permeate. The use of this membrane filtration prevents biomass washout, retaining a high culture density and allows for a high hydraulic throughput with minimal reactor volume requirement. Fabricating an automated control and monitoring system that includes fail safes to mitigate potential failures required repeated design integrations, test runs, and trial and error during operation. Figure 3 shows a schematic of the designed AnMBR process, while Figure 4 depicts the OPA unit.

The RAMS framework, which assesses a system's reliability, availability, maintainability and safety, was used to guide the design of the OPA architecture. These four considerations are not mutually exclusive and often affect each other. Figure 5 highlights examples of design considerations that improve one or more RAMS criteria. Notably, the compact and modular design, with ease of access to front-facing pumps, tubing, and sampling ports, was heavily influenced by considerations for *availability* and *maintainability*. During the design and fabrication of the OPA, many considerations were built into the system to minimize failures, downtime, maintenance, and prevent catastrophic failures. During operation, no catastrophic failures occurred; however, minor errors were encountered. These error events became learning opportunities to enhance the system's RAMS and inform future improvements in design.

IV. Results

The preliminary objectives of the investigation were to assess the OPA's ability to handle a progressively higher solids input. The OPA was operated for 436 days at USF including two successful dormancies, lasting 54 and 147 days with shutdown/startup simulation to test system reliability. The latter dormancy resulted from the COVID-19 pandemic. Ideal for simulating fecal waste[16], Complex Organic Particulate Artificial Sewage (COPAS) was used as the system influent with an increasing solids content of 1, 3, and 5%



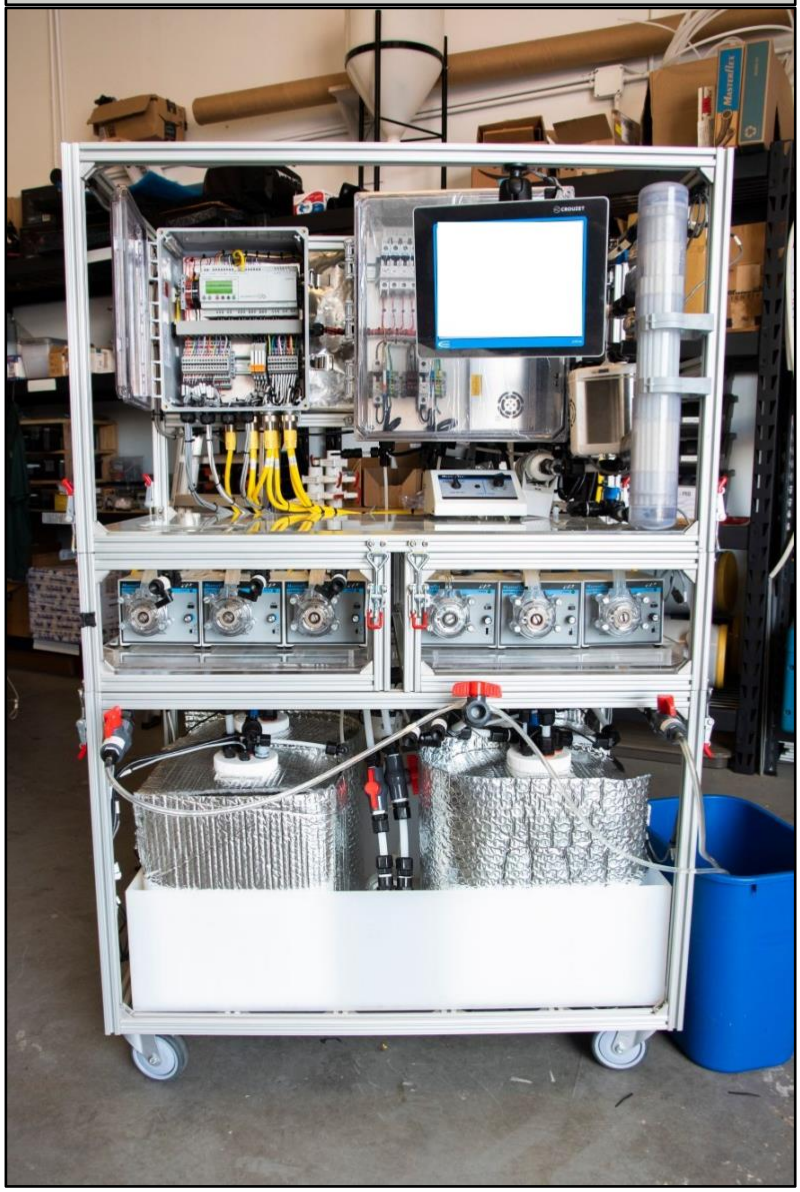


Figure 4. (top) Animated OPA Visualzation, (bottom) an OPA Unit.

(respectively represented as Stage A-C). Placed inside a refrigerator carboy, the influent was constantly mixed with a paddle mixer to overcome settling before being pumped into the OPA for processing.

The heterogeneous and particulate nature of the suspension waste stream resulted in a fluctuating influent stream (Figure 6). The high variability was beneficial in determining the OPA's capability in handling an unsteady input. As can be seen in Figure 6, the total solid concentration fed to the reactor during stage B and C at one point reached over 9% (90 g/L) and nearly 20% (200 g/L) respectively. These influent levels were three and five times the nominal influent, yet they still resulted in a consistently low effluent. It should be noted that there was a difference of multiple orders of magnitude in concentration between influent and effluent for several of the water quality parameters tested in this study.

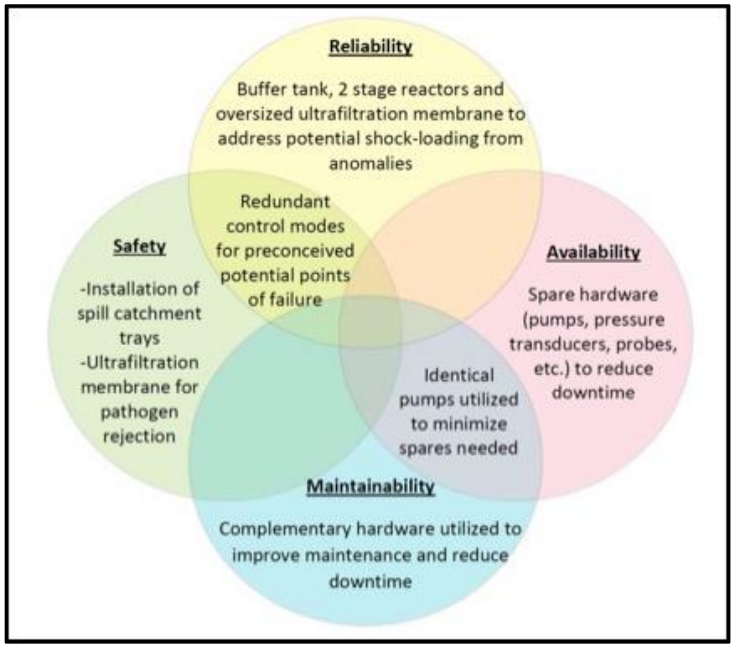


Figure 5. Venn Diagram of system design decisions that relate to the RAMS framework.

Although the influent varied, the OPA achieved substantial treatment and removal of both total and suspended solids (Figure 6), while achieving an average 94% removal of TSS and 99% for VSS. Theoretically, the effluent TSS should be near zero, as membrane filtration should reject all particulates less than 0.3 microns. However, in practice, biological regrowth on the permeate side (outside) of the membrane, due to the presence of soluble nutrients, result in the generation of secondary TSS. The TSS can be easily handled by downstream processes via conventional means such as cartridge filters.

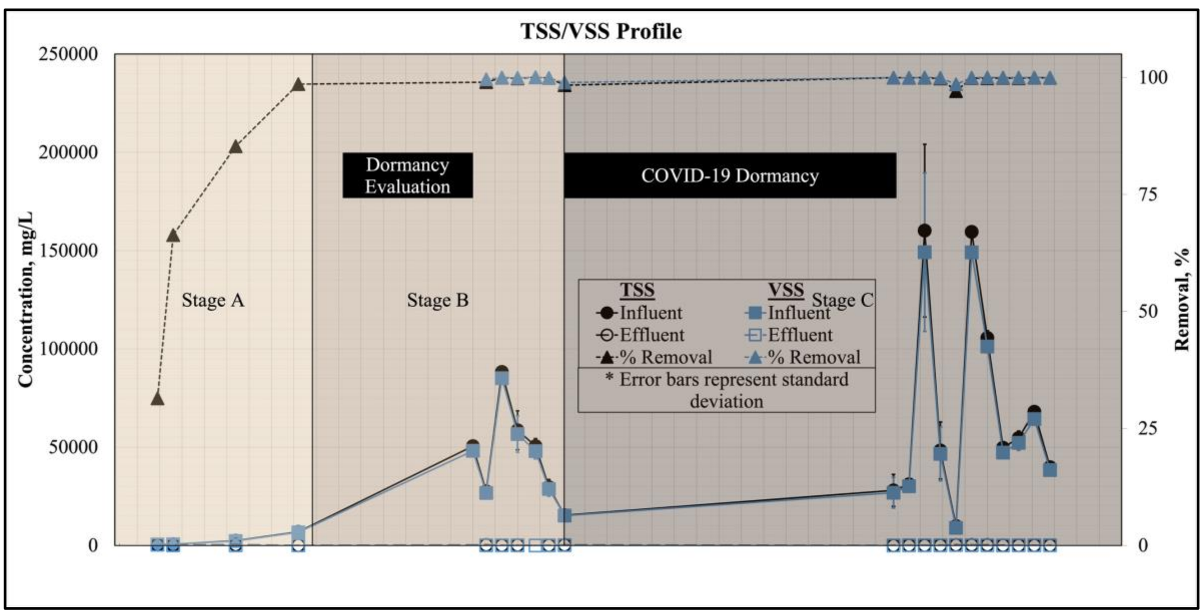


Figure 6. Total and Volatle Suspended Solids in OPA Influent and Effluent.

V. Conclusion

Preliminary data indicates that the OPA is capable of treating simulated fecal waste with progessivley increasing solids content up to 5% without any chemical input or aeration requirements. Figure 7 depicts the OPA as a candidate to fill the technology gap between *wet* and *dry* technologies. Continued operation will monitor and optimize long-term, sustainable operation, reliability, and raise system TRL. Next generation advances aim to expand system capabilities and address lessons learned, as well as future challenges. To address potential biological regrowth in the OPA effluent, permeate polishing with UV-LED will be examined. For enhanced solid breakdown, a thermal pretreatment stage will be introduced prior to the Stage 1 Reactor. To raise the TRL, waste treatment will shift from COPAS to real fecal waste and food waste. A twin OPA was fabricated and delivered to KSC for parallel and complimentary investigations. The second OPA at KSC will be integrated with downstream technologies for preliminary development of a comprehensive BLSS architecture suitable for EPB and long-duration missions.

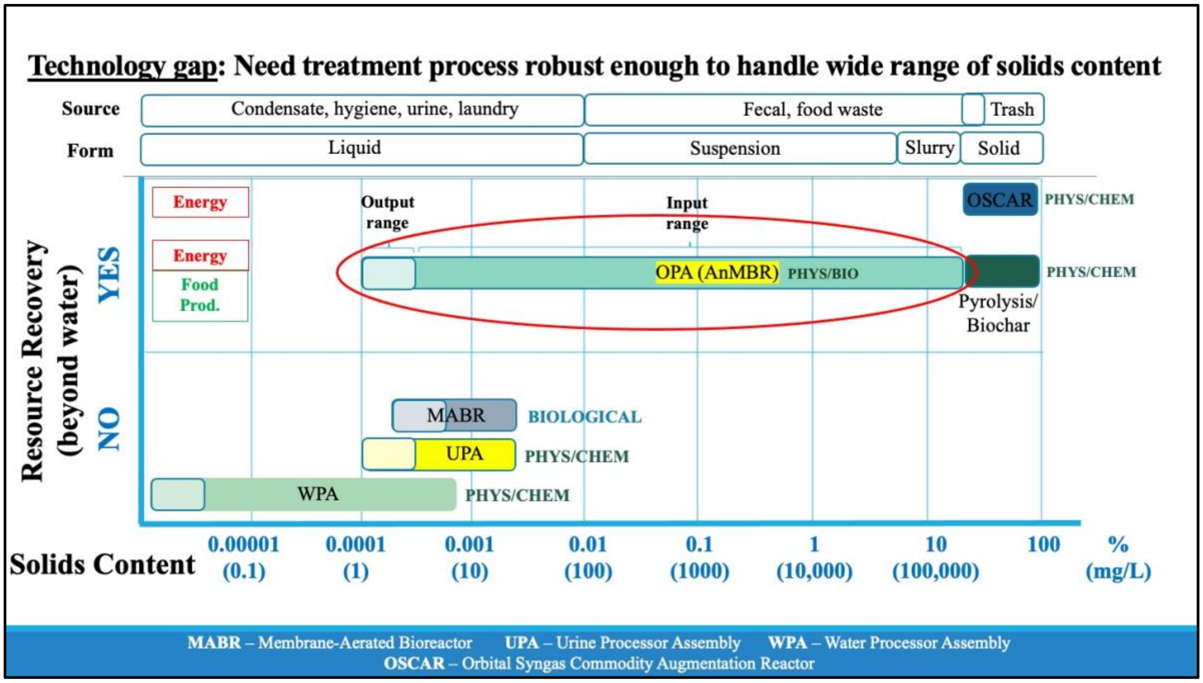


Figure 7. Applicable technologies based on solids content including the OPA filling in the technology gap and classified by resource recovery beyond water.

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