Lessons Learned from the Integration of Biological Systems in Series for Wastewater Treatment on Early Planetary Bases

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As humans begin to explore and build sustainable early planetary bases on the Moon and Mars, the crew will require environmental control and life support systems (ECLSS) that are capable of recovering key biogenic elemental resources from waste streams for reuse. Resupply from Earth during these long-duration deep space missions is not feasible; therefore, the requirement for advanced technologies is paramount to the success of these future missions. Under the National Aeronautics and Space Administration's (NASA) Advanced Exploration Systems (AES) program, the development of prototype bioreactors was established to help solve this resource recovery gap. The technology developed within the AES project utilizes three bioreactors to sustainably purify astronaut wastewater: An Organic Processor Assembly (OPA)/Anaerobic Membrane BioReactor, a Nutrient Processor Assembly (NPA) consisting of an PhotoMembrane BioReactor (PMBR), and a Suspended Aerobic Membrane BioReactor (SAMBR). In the early stages of the project, these subsystems were running independently for nominal and off-nominal testing and analysis. As the project progressed, the OPA and the PMBR were integrated as part of a larger bioregenerative wastewater purification system. Integration of these two advanced biological systems required the merging of different electrical and operational control systems. This paper describes the efforts required to link these systems as well as unforeseen issues that arose after integration.

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Lessons learned related to the integration of these two subsystems are presented and discussed.

Nomenclature

AES = Advanced Exploration Systems
ALiSSE = Advanced Life Support System Evaluator
ALS = Advanced Life Support
BLSS = Bioregenerative Life Support Systems
CDRA = Carbon Dioxide Removal Assembly
ECLSS = Environmental and Controlled Life Support Systems
ESA = European Space Agency
EPB = Early Planetary Base
EXPRESS = EXpedite the PRocessing of Experiments to Space Station
GAC = Granulated Activated Carbon
ISS = International Space Station
KSC = Kennedy Space Center
NASA = National Aeronautics Space Administration
NPA = Nutrient Processor Assembly
OPA = Organic Processor Assembly
PBR = Photo BioReactor
PMBR = Photo Membrane BioReactor
SAMBR = Suspended Aerobic Membrane BioReactor
USF = University of South Florida
UV = Ultra-violet
WPA = Water Processing Assembly

I. Introduction

BIOREGENERATIVE life support systems (BLSS), also referred to as Environmental Control and Life Support Systems (ECLSS), have been a topic of investigation for use in space since the early 1950's.[1] These systems are capable of regenerating essential resources as well as helping recover biogenic elements from waste-streams that can be reconstituted for specific use by the crew without the need for a costly resupply from Earth. To date, human spaceflight missions have either remained in close proximity to Earth, where resupply of essential resources has been a feasible option, or were short in duration, where resupply was not needed. As human missions venture deeper into space and their durations increase, resupplying the crew from Earth with essential resources becomes a less feasible and viable option. Therefore, the use of BLSSs in future long-term space missions is paramount to crew health, safety, and overall mission success.

Water management is one of the most important areas of life-support, since water contributes greater than 65% of the daily mass input for crew members.[2] Current water recovery technology on the International Space Station (ISS) relies purely on physicochemical systems and requires substantial inputs of energy and consumables.[2,3] Under NASA's Advanced Exploration Systems (AES) program and in collaboration with the University of South Florida (USF), prototype bioreactors were developed at Kennedy Space Center (KSC) to help solve this resource recovery gap as well as to close the loop on waste streams treatment in space habitats and on early planetary bases. The overarching goal of this specific project is to develop a closed loop bioregenerative architecture composed of multiple bioreactors and other modular technologies that is capable of purifying waste streams while the subsequent effluent and biomasses can be used for a multitude of purposes. In particular, the effluent, after being processed through these bioreactors, is intended to become a fertilizer source for food production purposes. Resource recovery from metabolic wastes provides a near closed-loop approach for sustainable food production. Organic wastes (i.e., fecal and food) offer a renewable source of carbon, nitrogen, phosphorous, water, and other trace elements to sustain food production. However, these high-strength waste streams are difficult to treat, due to factors such as heterogeneity, complexity, high solids content, and presence of pathogens.[4] Currently, there are no flight-ready technologies capable of treating mixed organic wastes, underlining a technology gap for future space missions.

The technology developed within this AES project utilizes three bioreactors to sustainably purify astronaut wastewater: An Organic Processor Assembly (OPA)/Anaerobic Membrane BioReactor, a Nutrient Processor Assembly (NPA) consisting of an PhotoMembrane BioReactor (PMBR), and a Suspended Aerobic Membrane BioReactor (SAMBR) (figure 1). In the early stages of the project, these subsystems were running independently for nominal and off-nominal testing and water analysis. As the project progressed, the OPA and the PMBR were integrated as part of a bigger bioregenerative wastewater purification system. As these bioreactor subsystems were designed independently of one another, they inherently had different electrical and software control systems. In order to build a nearly closed loop bioregenerative system, several bioreactor subsystems will require integration with one another. Integrating these subsystems into the greater bioregenerative architecture proved to be challenging as unforeseen issues arose once these systems were conjoined. Addressing and overcoming these architectural challenges is discussed and viable remedies are considered for continuation and evaluation of this bioregenerative system.

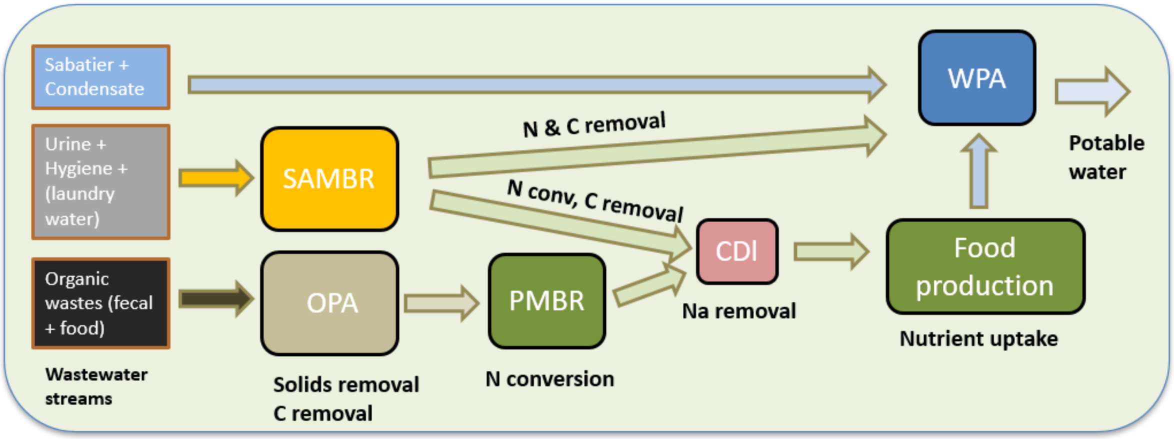

Figure 1. System architecture integration for sustainable wastewater recycling and resource recovery flow schematic.

II. Criteria for Bioreactor Design

Under NASA's Artemis program, the agency intends to return humans to the moon, thus marking another progressive step in the Space Age. These missions not only aim to maintain a continuous presence on the moon but will also serve to pioneer the way to Mars and ultimately, future long-duration space exploration and habitation.[5] Therefore, there are a multitude of properties and factors that need to be considered when designing BLSSs for space habitation. The *Advanced Life Support System Evaluator* (ALiSSE) metric, developed by the European Space Agency (ESA) simultaneously considers many of these criteria, including power, performance, energy, efficiency, robustness, reliability, and/or risk to humans, and crew time.[6] These considerations and criteria were heavily relied upon when the design and fabrication of the OPA and PMBR began. As this paper focuses on the integration of these subsystems as opposed to design optimizations of these individual systems, a description of each system will be provided before a description of system integration is discussed.

A. OPA

The main objective of the OPA is to process high-strength solids and complex organics found in fecal and inedible food waste and produce an effluent capable of further downstream treatment that would otherwise overload downstream systems.[5] An anaerobic membrane bioreactor (AnMBR), a hybrid technology coupling anaerobic digestion with membrane filtration, forms the heart of the OPA. As part of a closed-loop bioregenerative resource recovery architecture, the OPA was designed for an early planetary base (EPB) scenario to aid in closing the resource recovery loop, thus decreasing resupply dependence. For purposes of this OPA prototype, a system sized to treat the fecal waste of a crew of four was selected as the design criteria as the Orion Multi-Purpose Crew Vehicle (MPCV), that will be used during the Artemis program and likely future deep-space missions, is designed for such. Furthermore, the generation of the combined fecal waste and flush for a crew of four is estimated to be 2.5 Liters/day (L/d) and was a parameter considered when designing the OPA.[4,8]

BLSS design is greatly affected by available space in future space habitats and volumetric restrictions must be considered. In regards to these spacing constraints, the hardware that will house BLSSs for future long-term deep-space exploration is still being investigated as there is not a one-size fit all approach to these systems. The current approach on the ISS is a standardized racking system known as EXpedite the PRocessing of Experiments to Space Station (EXPRESS) racks. As the OPA was designed to be a future BLSS technology, a target form factor needed to be identified as a suitable surrogate due to the lack of future ECLSS housings. Therefore, the EXPRESS rack system is the most current and appropriate as no future form factors have been officially announced.[4] The OPA was designed with this spacing criteria in mind and currently fits within the dimensional aspects of the EXPRESS rack (figure 2).

Considering the treatment of high-strength waste, volumetric restrictions, and commercially available resources, a series of three 20L carboys were fabricated for the system's design. A two-stage reactor system, reactor-1 and reactor-2, was designed to decouple and optimize the acidogenic and methanogenic phases of anaerobic digestion, with the biogas collected from both reactors.[4] The digested reactor-2 contents then travel through a membrane module where the permeate is then collected in a separate tank while the rejected constituents consisting primarily of biomass and undigested solids is recycled back into reactor-2. In order to aid in the hydrolysis of high strength solids, two heating wands were installed in the buffer tank and reactor-1. This was intended to not only help with hydrolyzing solids but also provide warmer temperatures for the microbes in reactor-1 thus increasing digestion efficiency.

The control system which is based on a programmable logic controller (PLC) runs the systems peristaltic pumps and monitors the capacitance level sensors located on all of the subsystem carboys. The PLC also communicates with the Human Machine Interface (HMI) which allows a user to interact with the system to turn the system on and off, perform sampling of individual tanks, view general processes and logged errors, and sends out remote notifications on system events and statuses. The PLC uses Crouzet-Soft automation software that runs function block diagram coding while the HMI utilizes Crouzet Touch Soft software that runs graphical programming/configuration tool coding. The system is plugged into a 750 watt battery backup universal power supply (UPS) to keep the system operational during power blackouts and brownouts.

Figure 2. OPA within the EXPRESS rack skid.

B. PMBR

Algal-based BLSSs are promising candidates for human life support due to their fully edible biomass, ease of handling, and fast growth rates. Since the beginning of spaceflight, algae have been intensively studied for this purpose, even before the first human flew in space.[3] One major advantage of utilizing algal biosystems is that algae can efficiently remove CO_2 through the rapid production of algal biomass which can be greatly beneficial for space habitat applications. Furthermore, coupling wastewater treatment with CO_2 biofixation provides a massive benefit for helping close the waste stream loop in space applications.[9] Therefore, the PMBR is primarily tasked with converting high concentrations of fertilizer nutrients in the waste streams to algal biomass and relieving some of the treatment burden from the downstream processes like the Water Processing Assembly (WPA). PMBR effluent can be sent to the WPA for further treatment to potable water or used as a fertilizer water stream that is suitable for downstream plant growth.[10] In particular, this requires a reduction of ammonia species (i.e., NH_3/NH_4+) concentration as higher-order plants cannot tolerate the high concentrations found in these streams.[11] An added benefit from the PMBR is atmospheric regeneration; algae provide a sink for generated carbon dioxide, reducing the removal burden of CDRA (Carbon Dioxide Removal Assembly, a current ISS ECLSS), and produces oxygen needed for crew respiration.

Chlorella sorokiniana was evaluated as the algal culture for use in the PMBR because it was shown to have high potential for NH_4 removal from urine-derived wastewater.[12]

The performance of algal-based BLSS's is determined by biotic factors (i.e. algal culture properties) and abiotic factors (i.e. the environment and cultural conditions – light distribution, CO_2 concentration, pH, temperature, aeration). In the beginning stages of this project, a 3-inch diameter cylindrical photo bioreactor (PBR) was designed and tested. After initial testing, it was realized that a maximum algal culture density of 0.9 g/L was achieved in this PBR subsystem, which is lower than the maximum density for this algal species attained in a short light path flat-panel PBRs which is around 2 g/L.[12,13,14] Furthermore, due to the cylindrical design, it was observed that the light source did not uniformly illuminate the entire length of the PBR, and could only illuminate 50% of the surface area of the algal PBR. These findings suggest that the algal culture in the cylindrical PBR may be light limited due to self-shading within the inner layers of the PBR.[15] Therefore, these and other limitations of the cylindrical PBR lead to a redesign to a flat-panel PBR configuration (figure 3). The newly designed PBR was able to plug directly into the existing quick disconnects for fluid lines to the membrane, influent feed, effluent tank, and CO_2 control boxes.

Figure 3. The cylindrical PBR was redesigned into a flat-panel PBR.

The external sensor suite consists of pre- and post-system CO_2 sensors, a Dissolved Oxygen (DO) sensor, an ammonia probe sensor, capacitance level sensors, and various Photosynthetically Active Radiation (PAR) sensors. The internal sensors consist of a dissolved CO_2 sensor for real time concentrations within the reactor, a pH sensor, a float-switch sensor for monitoring liquid levels, and temperature sensors. Additionally, there is an external heating loop that maintains the reactor contents at a specifically desired temperature. The electrical, control and monitoring system is run using the Opto 22 control and monitoring hardware and software. Like the OPA, the PMBR utilizes peristaltic pumps to move liquid through the system and perform membrane maintenance events. The light source is a LED light set to a specific intensity and utilizes a basic timer for a desired on-off photoperiod. The system is also plugged into its own 750 watt battery backup UPS to keep the system operational during power blackouts and brownouts.

III. Systems Integration

Systems integration is essential to the development of any large life support system and provides an organized, sensible, accountable, and workable approach to otherwise very difficult problems and issues found in life support systems.[16] The overall goal of this specific AES project incorporated the integration of several biological and physio-chemical subsystems into a greater bioregenerative purification system. After individual subsystem testing and optimization of the OPA and PMBR occurred, the team decided to begin their integration with one another. As these two subsystems operated on different electrical, control, and monitoring hardware's and software's, it was evident that new architectural implementations were needed to properly integrate them. The first step was to implement an integration plan that ensured reliability and accounted for individual subsystem failures.

C. System Integration Planning

As the OPA was designed to treat the generation of the combined fecal waste and flush for a crew of four so was the PMBR. Therefore, the PMBR is capable of processing 2.5 L/d of effluent from the OPA. Since these two systems are capable of treating the same volumes of simulated waste, one could essentially just connect the OPA's permeate line to the PMBR's influent line and run them as a single system. However, these two subsystems are still prototypes and prone to unforeseen failure events, so it was decided to design an intermediary system between the OPA and the PMBR to ensure overall system robustness and reliability. Considerations such as individual system failures, power outages, over or under-production of permeate from either subsystem, and extended periods of no human observation or interactions needed to be factored into the intermediary system design. It was decided to design a Reservoir Tank (RT) that would act as a failsafe between these two subsystems and would have a logical system capable of communicating with both systems to circumvent failure or off-nominal events.

To ensure ample room for error, it was decided that the RT would be 20L, to be similar to the plastic carboy tanks in the OPA. This would allow for plenty of OPA permeate to build up and act as a buffer during off-nominal operation. In the event that the OPA stopped producing permeate or if the PMBR stopped pulling permeate from the RT, a system needed to be designed to ensure that the OPA did not overflow the RT or that the PMBR did not run dry due to the lack of OPA permeate production. Therefore, a liquid level sensing system was designed on the RT utilizing capacitance level sensors. On the OPA, each tank has a high- and low-level capacitance sensor that communicates with the systems monitoring controls which subsequently will turn on various pumps to move liquid properly through the system. The same logic would be applied to the RT with high- and low-level sensors communicating with both systems. It was decided that the low-level sensor on the RT would communicate with the OPA while the high-level sensor would communicate with the PMBR. This was done so that when the high-level sensor is activated, a signal is sent to the OPA's PLC to tell the system to stop producing permeate. In turn, the low-level sensor would communicate with the PMBR's Opto 22 monitoring system of low liquid levels in the RT to tell the system to stop pulling upstream permeate (figure 4).

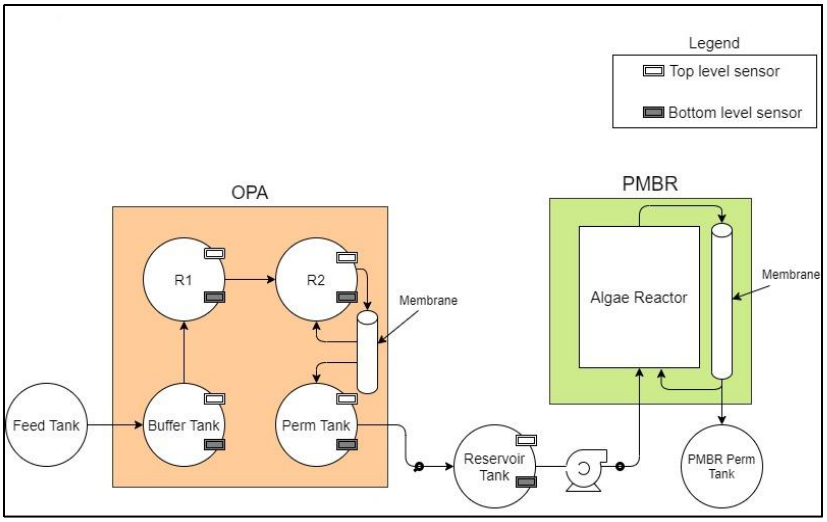

Figure 4. OPA and PMBR connection flow diagram.

D. System Integration Testing and Issues

One of the first integration steps was to match permeate flow rates of both systems. This was achieved by running each system's product pumps for a given time and then measuring the resultant volume and adjusting the manual flow controller on each pump to the desired flow rate. The desired flow rates for both systems was 2.5 L/day. However, we adjusted the PMBR's flow rate to be slightly lower than OPA's (2.4 L/day) so that there will always be a higher buffer volume in RT. Ultimately, due to the design implementations of RT's level sensors, the PMBR's flow rate drives both systems flow rates.

After system integration occurred, the OPA was turned on while the PMBR remained off in order to build up a sufficient buffer volume of OPA permeate in the RT. It was decided that there should be at least three days worth of permeate volume in RT to ensure that if any off-nominal issues arose for the OPA, that the downstream PMBR would be able to operate continuously while the issue was resolved. Once the adequate OPA buffer volume was achieved in the RT, the PMBR was turned on and both systems operated continuously and processed 2.5 L/day.

Due to the interconnectedness of components within systems, it is possible for an event at one part of the system to affect other parts in unintended ways, through unanticipated channels.[17] For example, after three days of continuous system integration and operation, the OPA system encountered a series of issues related to system power consumption. A facilities power supply issue caused a software and PLC communication error which led to a system pump acting independently of the control system. Furthermore, about a week later, the UPS for the OPA failed and caused the system to enter a stasis mode where it did not produce any permeate. These power fluctuation issues continued to occur until it was discovered that the heating wands in the buffer tank and reactor-1 demanded more power than was available from the facilities outlets. During this power supply investigation, the system encountered multitude issues related to pumps running independently of the PLC. These power fluctuation issues resulted in multiple downtime periods where the OPA was not able to produce enough permeate to feed the downstream system, which in turn translated to multiple stoppages in PMBR operations.

IV. Lessons Learned

It can be generalized that the sequence of system integration planning, analysis and then testing must be performed whenever there are dependencies between systems. Without these steps, the risks associated with instabilities associated with system coupling remain unknown until after integration, sometimes until well after deployment.[18] The ongoing testing of these integrated systems provides insights on the difficulties involved in connecting complex advanced life support systems while highlighting areas that can be improved or altered in future iterations. Advances in system-to-system communication, improved overview software that can observe both systems simultaneously, and having a better understanding how biological interactions effect downstream processing will provide lessons to help strengthen future integrations of these types of bioregenerative technologies.

E. System-to-system Communication

One of the main lessons learned after integration of these two subsystems was the need for software capable of system-to-system communication. In the current configuration, there is no connection between each of the subsystem's control and monitoring systems. From a logic standpoint, these systems do not communicate or send information between one another and the only way these two systems interact is from a tertiary perspective via the high and low level sensors on the RT. If system-to-system communication was established, information regarding individual subsystem permeate production, individual system errors, and other vital monitoring information could be shared between subsystems. Communicating this information between systems would provide the ability of quickly identifying process deviations and then the individual control systems could implement program modifications to prevent up-and-downstream processing stoppages.

F. Primary Overview Software

The need for a primary overview software arose from the lesson learned regarding the system-to-system communication need. Additionally, from a systems operator perspective, there is a need for a 'master-style' overview software that would allow a user to monitor and control parameters of each individual subsystem without having to utilize different software programs for those individual subsystems. This would allow a user to modify a multitude of systems conditions from a centralized location and view the larger system processes as a whole. Furthermore, this would also make remote accessibility to the larger system more centralized in the event that a user was off site and needed to modify a system process across both systems.

G. Biological Effects of Downstream Processes

Another lesson learned was the need for a broader understanding of how biology affects downstream processes. For example, with the addition of the RT to act as a buffer between subsystems and allow a programmable logic step with regards to pseudo-communication between subsystems, an external tank was added between the OPA's permeate production step and the PMBR's feed influent step. This tank provided a new reservoir where the OPA's permeate resides until the PMBR's control system instructs its feed pump to uptake 'feed'. From a biological perspective this new tank provides the potential for microbial regrowth to occur which can alter the water chemistry of OPA's permeate post-production. This in turn can cause a lack or excess of unintended constituents that will be introduced into the PMBR which can alter the algal growth and processing characteristics in unknown ways. In future iterations of these technologies, this RT tank would not exist as the intent is to have the OPA's product line feed directly into the PMBR's influent feed pump line. However, it is important to characterize each tank's water chemistries to better understand how this potential microbial regrowth in the RT effects the chemistry of downstream processes.

Furthermore, post-processing modifications can be put in place after permeate production to help eliminate microbial regrowth or reduce organic chemicals. Ultra-violet (UV) disinfection units can be put in place to help reduce the potential of microbial regrowth. Additionally, granulated activated carbon filters can run in tandem with UV polishing units post-processing to help reduce organic chemicals, chlorine, and unwanted micropollutants. Understanding how these post-processing modification alter water chemistries and, in turn effect the biology in these systems will allow for the future iterations of these systems to become more resilient and robust.

V. Conclusion

The primary goal of NASA's Advanced Life Support (ALS) program is to develop systems that can support the lives of astronauts for the duration of extended missions. Accomplishment of NASA's goal requires the development of systems and tools for sustaining human life for periods of several months to several years.[19] BLSSs are candidate systems that can regenerate valuable biogenic resources from astronaut waste streams for reuse when resupply missions from Earth are not feasible. These systems are complex in nature and require integration into not only other life support systems but the overall mission architecture as well. Integrating complex systems requires a fundamental understanding of how each subsystem works, especially when biological entities are part of their processing scheme. Given the uncertainties of how to construct viable bioregenerative life support system for either short- or long-term operation in space, ground-based experimentation with a wide variety of approaches and with varying technological support strategies are not premature, but essential if human space exploration and habitation outside the Earth's biosphere is to be viable even decades in the future.[20] As the operation of these two integrated systems continues, the evaluation of the lessons learned and the next steps will begin to be implemented. Discussions are on-going to develop and or implement a 'master-style' overview software that can perform all the functions that will be needed to remotely operate and monitor these complex systems while allowing for better system-to-system communication. Furthermore, the continued water chemistry analysis of these integrated sub-systems will gain a better understanding of how off-nominal events effect the system as a whole. Future architectural changes to these systems to optimize performance and robustness will also affect both water chemistries and systems biology which will need to be evaluated when that happens. It is with the continuation of ground based testing, integration, and lessons learned from systems like the OPA and PMBR that will allow humans to develop resilient and robust biological technologies that will help NASA achieve its ALS program goals.

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