Human Exploration Beyond Low Earth Orbit: Staged Evolution of BLiSS Technologies

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Bioregenerative Life Support Systems (BLiSS) provide sustainable life support to human crews living in lunar and Martian surface habitats. BLiSS architectures are complex and will need to evolve in stages of maturity as more inhabitants are deployed to surface habitats. In the regenerative Environmental Control and Life Support Systems (ECLSS) currently used on ISS with 4-6 inhabitants, air, food, and water are supplied from Earth, waste is stored and returned to Earth, and only air along with a portion of water are recycled onboard. Thus, such a regenerative ECLSS architecture supports short duration (30-day) missions and represents an initial or 'survival stage' of life support that requires frequent resupply and is not economically or technically viable for long-duration missions. To meet the objectives of NASA's Moon-to-Mars (M2M) Architecture, the development of a four-stage BLiSS architecture was designed and proposed. A second 'intermediate stage' still relies on food resupply but regenerates air, water, and recycles waste. This stage utilizes dedicated, self-sustaining bioreactors to process urine, hygiene/laundry water, metabolic waste slurries (i.e., feces, food waste), and trash to produce potable water and recover essential resources (e.g., fertilizer, CH_4, CO_2, and N_2). A third, 'sustainability stage' utilizes recycled water and nutrients to produce a major portion of the habitat food supply using plants, which provide O_2, removes CO_2, and performs additional water purification. Finally, a fourth, 'mature stage' uses recycled feedstocks from BLiSS (i.e., nutrients, water, CH_4, CO_2, etc.) and additional dedicated bioreactor systems to support *in situ* biomanufacturing of value-added products (e.g., fuel, proteins, medicines, construction materials).

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Acronyms and Nomenclature

AnMBR	=	Anaerobic Membrane Bioreactor
APH	=	Advanced Plant Habitat
APMBR	=	Anaerobic Phototrophic Membrane Bioreactor
BLiSS	=	Bioregenerative Life Support System
BPA	=	Brine Processor Assembly
CDRA	=	Carbon Dioxide Removal Assembly
CEEF	=	Closed Ecological Experiment Facility
CLPS	=	Commercial Lunar Payload Services
CTSD	=	Crew and Thermal Systems Division
ECLS	=	Environmental Control and Life Support
ECLSS	=	Environmental Control and Life Support Systems
EPB	=	Early Planetary Base
ESA	=	European Space Agency
ESDMD	=	Exploration Systems Development Mission Directorate
EVA	=	Extravehicular Activity
HLS	=	Human Lander System
ISS	=	International Space Station
M2M	=	Moon-to-Mars
MABR	=	Membrane Aerated Bioreactor
MABR-PAX	=	Membrane Aerated Bioreactor (MABR) and Pancopia AnammoX (PAX)
MCO	=	Mars Campaign Office
MELiSSA	=	Micro-Ecological Life Support System Alternative
NASEM	=	National Academies of Science, Engineering, and Medicine
OSCAR	=	Orbital Syngas Commodity Augmentation Reactor
PMBR	=	Phototrophic Membrane Bioreactor
SAMBR	=	Suspended Aerobic Membrane Bioreactor
TCCS	=	Trace Contaminant Control System
UPA	=	Urine Processor Assembly
WPA	=	Water Processor Assembly

I. Background: NASA's Moon to Mars Architecture

Recently, the NASA Exploration Systems Development Mission Directorate (ESDMD) released its plan for sustained exploration.[1] The Moon to Mars (M2M) Architecture Definition Document describes a sustained lunar presence as a primary objective. It calls for the development of an initial surface habitat that expands from the Human Lander Return segment of exploration, where two crew members would live and work on the lunar surface for a minimum of 7 to 33 days with logistics resupply. The subsequent Foundational Exploration segment calls for the development of a long-duration deep space, partial-gravity crew habitat on the Moon, from which the crew can conduct exploration sorties in EVA suits. The Sustained Lunar Evolution segment aims to accomplish objectives of increased global science capability, significantly increase the size of the lunar population, and increase the large-scale production of goods and services derived from lunar resources. These objectives will require increased access and use of ISRU-produced materials and/or consumables, demonstration of bioregenerative ECLS subsystems, demonstration of plant growth subsystems, as well as increased infrastructure and crew transportation systems to a permanent lunar outpost. The National Academies of Science, Engineering, and Medicine (NASEM) *2023 Decadal Survey: Thriving in Space*[2] reemphasizes the need for NASA to invest in bioregenerative life support and in-space manufacturing, such as biomanufacturing and 3D printing that our team been performing since 2019 under the ESDMD Mars Campaign Office (MCO). NASA's *2024 Sustainability Beyond Earth*[3] policy directive further expresses the necessity of conducting more work on bioregenerative systems. Each of these policy directives and mission architecture plans drive NASA towards implementing a sustainable, self-sufficient spaceflight architecture for longer duration missions.

II. Introduction

Bioregenerative life support systems (BLiSS) provide sustainable life support to human crews living in lunar and Martian surface habitats. They are closed ecological systems composed of processors (e.g., plants and algae) that produce oxygen, provide food and purify water, decomposers (e.g., fungi and bacteria) that recycle wastes, and storage reservoirs (e.g. cabin atmosphere, food and waste storage, nutrient reservoirs) that mimic the Earth's ecosystems.[4-7] Their primary goal is sustaining humans during long-duration exploration missions without relying on constant resupply from Earth. BLiSS subsystems can be studied at many scales (Figure 1): Single organism (i.e., plant-microbiome relations), population (i.e., APH/Veggie plant chambers, bioreactors), subsystem (i.e, Biomass Production Chamber demonstrating crop production and controlled environment agriculture technologies), integrated human-rated system (i.e., life support for a crew of 4 during 365 days in China's Lunar Palace 1), self-sustaining artificial ecosystem (i.e., life support for a crew of 8 during 2 years in Biosphere 2), and ultimately planet (i.e., the Earth's ecosystems).[5-16] Results from these studies inform on the physiology of organisms, the performance of technologies and integrated subsystems, and the overall sustainability of components to be included in artificial life support systems.[4,6,14,17]

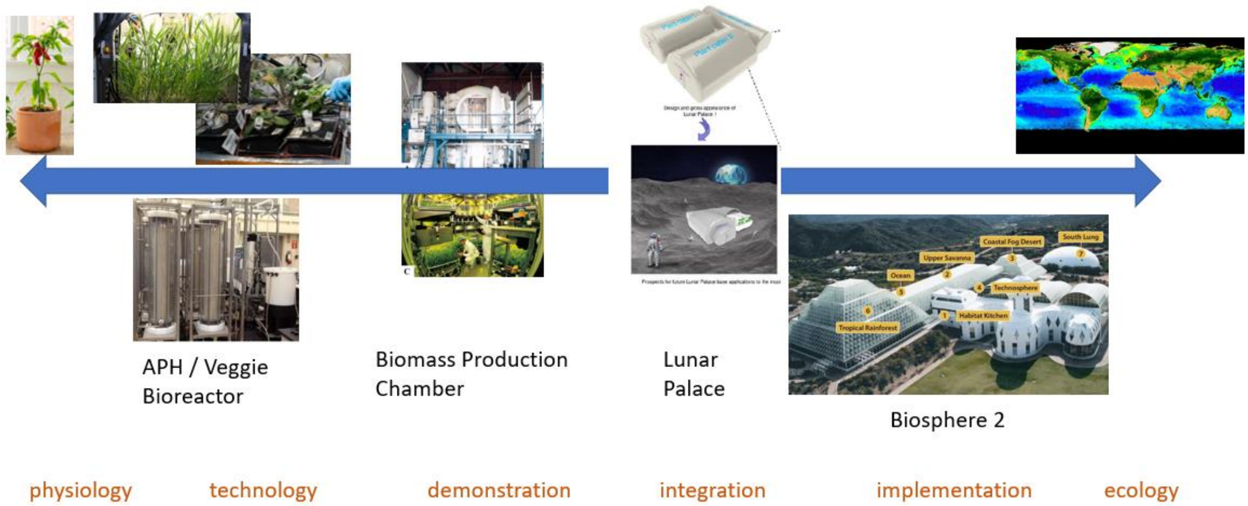

Figure 1. BLiSS subsystems can be studied at many ecological scales. *These scales are organism, population, subsystem, integrated human rated system, self-sustaining ecosystem, and natural ecosystems (Earth).*

The overall goal of bioregenerative life-support is to design and build sustainable, artificial ecosystems within the limited mass, power, and volume constraints of a surface habitat that can be deployed on the Moon or Mars.[17-18] Important steps toward the development of operational BLiSS have been demonstrated using human-rated, ground-based, proof-of-concept demonstrations in the last decades: the Russian Bios-3 facility (crew of 3 humans), the privately funded Biosphere-2 (crew of 8 humans), the Japanese Closed Ecological Experiment Facility (CEEF) (crew of 2 humans and 2 goats), and the Chinese Lunar Palace 1 (crew of 4 humans).[6-8,10,11] Although these efforts have included nearly 100% closure of the food production, air revitalization, water purification and overall environmental control functions of a BLiSS, most did not completely recycle minerals from plant and human wastes back to the primary producers (plants). In Bios-3, feces were dried and stored, and the reclaimed water was recovered as water vapor.[7,8] In CEEF, waste recycling included carbonization and incineration of feces and urine from the crew and goats, as well as from inedible plant material.[8] In the Lunar Palace 1, a portion of the inedible plant biomass was incinerated, and aerobic composting was used to degrade a mixture of crew feces and inedible plant biomass into an organic fertilizer.[10,11] In the ESA Micro-Ecological Life Support System Alternative (MELiSSA) Project, CO_2, organic wastes, and wastewater are recycled using biological, chemical, and mechanical processes into resources (i.e., O_2, water, minerals) to produce food, but these processes have only been demonstrated using a mock-up crew composed of rats to mimic human respiration and activities.[19] In Biosphere-2, human feces and urine, as well as animal wastes and inedible biomass from crops were recycled by a constructed wetland system consisting of aquatic plants. The lack of complete waste recycling in most of these demonstrations highlights a significant gap in bioregenerative life support recycling technologies, as organic wastes were often stored, incinerated, or composted, leading to the loss of valuable resources and energy and thereby preventing the development of completely closed-loop ecosystems.[8,11-14]

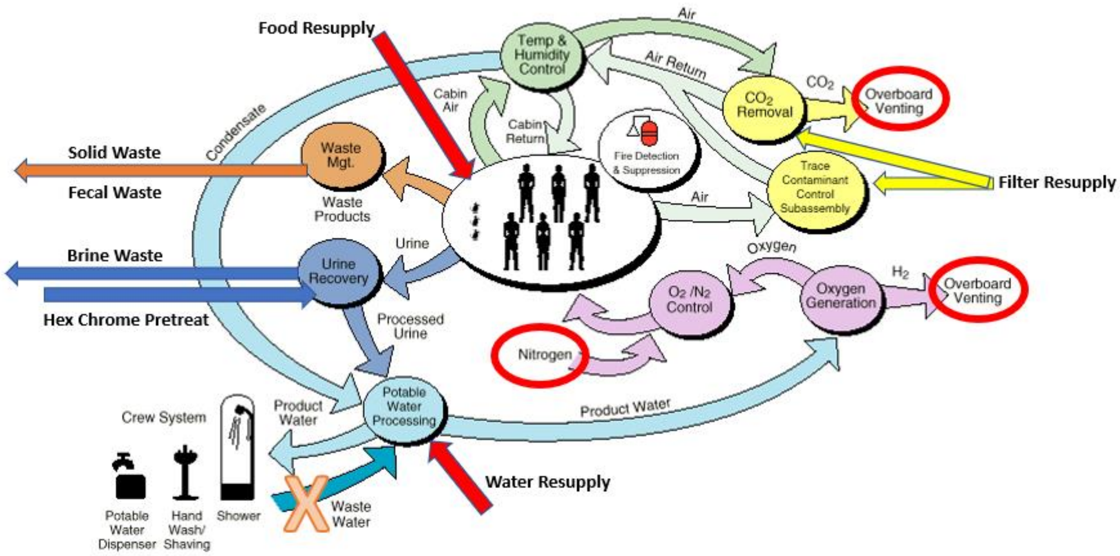

Figure 2. The regenerative ECLSS aboard the ISS. *The ISS ECLS system architecture is a starting point for the design of bioregenerative ECLS to be deployed in lunar and Martian surface habitats.*

III. State of the Art: ISS Regenerative ECLSS

The current ECLSS aboard the ISS (Figure 2) and other spacecraft is adequate for short-term missions but would need significant improvements to support the long-term objectives of the M2M Architecture because it relies on extensive resupply, storage, and venting.[20-23] Current water recovery and purification systems aboard the ISS are partially closed-loop, requiring constant resupply (e.g., food, water, nitrogen, hexavalent chromium for urine pretreat, sorbents, and replacement polishing beds) for the Carbon Dioxide Removal Assembly (CDRA), the Trace Contaminant Control System (TCCS), the Urine Processor Assembly (UPA), and the Water Processor Assembly (WPA). It also requires waste disposal (e.g., brine, solid and fecal waste) and suffers from losses of CO_2 and H_2 from venting when the Sabatier reactor is not operable. The first phase of the ISS water purification occurs in the UPA, which processes urine using a toxic hexavalent chromium and flush water pre-treat, followed by vapor pressure distillation, generating non-potable water along with brine wastes stored as a solid puck. The Brine Processor Assembly (BPA) recovers membrane technology and evaporation to recover water from the brine. The WPA polishes recovered water from the UPA, hygiene water, Sabatier water, and cabin condensate using ion-exchange membranes to provide potable water. It is important to note that the ISS water recovery system had demonstrated a 98% recovery of water; however, a significant amount of water is lost in solid waste (e.g., towels, fecal) that is not recovered. For future surface missions, the number of waste streams is expected to increase with the addition of facilities such as showers, laundry, and other hygiene operations. These waste streams will have different characteristics (e.g., surfactants, microfibers) and will increase the demand for consumables, as well as possibly require new treatment processes.

IV. Staged Surface Habitat Evolution

As discussed in Section I, the M2M Architecture calls for the implementation of sustainable habitation capabilities to support lunar missions. Yet this is not feasibly possible with current technology in a single launch vehicle. NASA has outlined a series of 10 Artemis missions to build out and expand the lunar habitat.[24,25] These missions start as general exploration with Artemis I at 25.5 days, and II at 10 days. Then expand to more ‘camping trip’ models in Artemis III-IX with consistent 30-day missions with construction elements being brought with the human lander system (HLS) and commercial lunar payload services (CLPS). Artemis X, planned for 2035, is designed to use the SLSL Block 2 design with a mission duration less than 180 days. It is in 2035 when the lunar habitat is expected to transition from construction to sustainability, providing a permanent habitat for humans. This transition time will be critical for transitioning regenerative ECLSS from simple 30-day missions to complex, sustainable, bioregenerative

ECLSS technologies supporting longer duration missions. Therefore, an evolving BLiSS life support architecture employing both physicochemical and bioregenerative technologies was developed to meet the objectives of a lunar habitat during the early and mid-stage exploration segments as described. The design of an evolving bioregenerative-based ECLSS was developed using the following assumptions:

1. The partial gravity habitat will be built in stages.
2. The initial stages will focus on survivability, mid stages on construction, and later stages on sustainability.
3. Dormancy periods will occur prior to Artemis X, requiring system stability and robust design.
4. Crew size will evolve from 2 to 4 humans - eventually larger in a sustainable lunar outpost.
5. Vehicles and habitats will have different systems for different missions.
6. Resupply must be minimized and eventually eliminated for Mars.
    a. Food – grown rather than brought.
    b. Waste – treated and recycled rather than collected/stored.

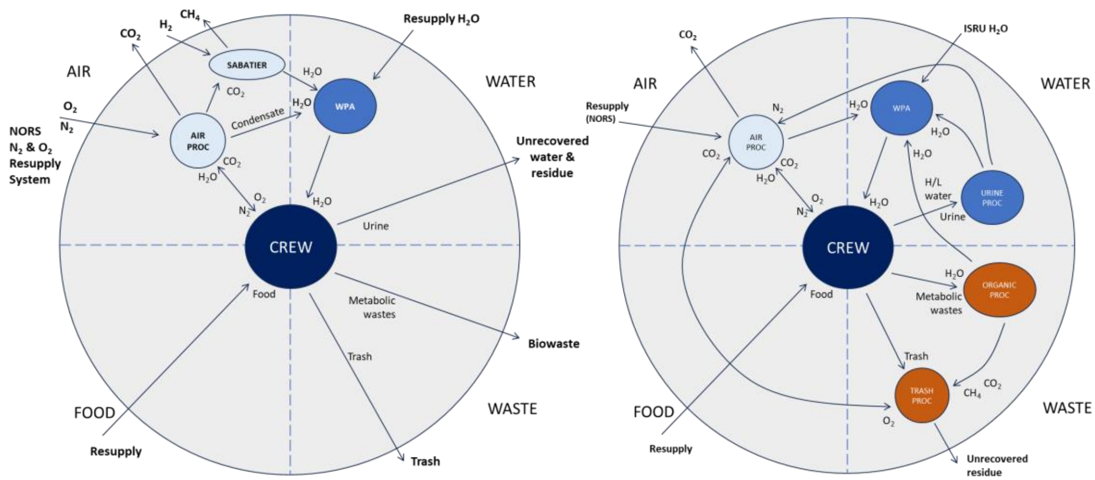

Figure 3. Survival and Intermediate Stages of Habitat Evolution. *The Survival Stage focuses primarily on Air and Water Recycling. The Intermediate Stage implements bioregenerative/physicochemical technologies to recycle metabolic wastes.*

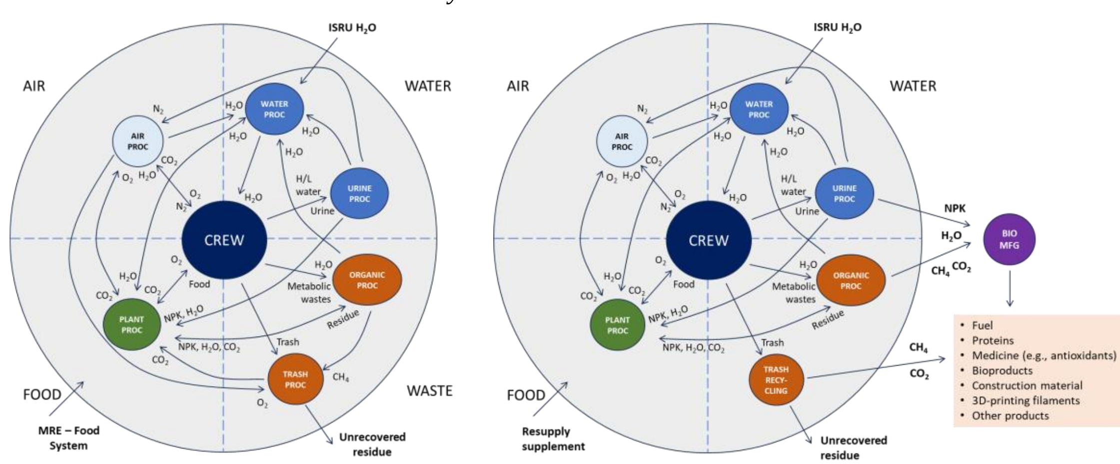

Figure 4. Sustainable and Mature Stages of Habitat Evolution. *The Sustainable Stage focuses primarily on Food Production, as well as Air, Water, and Metabolic Waste Recycling. The Mature Stage implements additional bio-manufacturing technologies to establish a self-sustaining Lunar Outpost.*

The **Survival Stage** (Figure 3, Left) uses the ISS ECLSS regenerative technologies for air and water processing. It requires resupply of N_2, O_2, H_2, food, and water. It also relies on the storage/disposal of unrecovered water and residue, biowaste, trash, as well as venting of CO_2 and CH_4. The **Intermediate Stage** (Figure 3, Right) still relies on resupply of N_2, O_2, and food, but utilizes ISRU water, and implements recycling technologies for metabolic wastes. This stage requires storage/disposal of unrecovered residues and venting of excess CO_2.

The **Sustainable Stage** (Figure 4, Left) incorporates bioregenerative crop production that is supplemented by a thermostabilized food system[18], but is essentially sustainable for a crew of 4. The **Mature Stage** (Figure 4, Right) implements additional technologies for biomanufacturing using byproducts (e.g., nutrients for other bioreactors, excess water, CH_4, and CO_2) from the BLiSS architecture of the habitat. The products of biomanufacturing include fuels, medicines, construction materials from biowaste, novel 3D printed filaments, etc. The **Mature Stage** also allows increased growth of the population of the habitat until a mature Lunar Outpost can be established. Biomanufactured products from the **Mature Stage** will also support the development of a vibrant cislunar economy.[14]

V. Waste Recycling Technologies to Support M2M Objectives

Our team (Pickett *et al.* 2020) previously identified that robust and reliable water purification systems will be required to sustain life during long-duration exploration missions.[26] During a 30-month exploration mission (Artemis III-IX), it was determined that one crew member will consume 2250 kg of water and 1359 kg of food and generate 1612 kg of metabolic wastes and 4156 kg of respiration and hygiene water. Thus, life support systems must treat and optimize water recovery from a waste stream of 5768 kg per crew member over a 30-month mission.

Numerous advanced water recovery systems have been integrated and tested by the Crew and Thermal Systems Division (CTSD) at the NASA Johnson Space Center. Verostko *et al.* (1992) tested a system sized for a four-person crew consisting of a two-stage, aerobic, trickling filter bioreactor that oxidized organics; a reverse osmosis system that produced potable water and a photocatalytic oxidation system that removed organic impurities.[27] Pickering *et al.* (1998) used biological and physicochemical processes to generate potable water from a combined wastewater stream consisting of waste hygiene water, urine, and humidity condensate for 91 days in support of the Lunar Mars Life Support Test Project.[28] Campbell *et al.* (2003) demonstrated the capability of an integrated advanced water recovery system to produce potable quality water for six months from a wastewater stream consisting of urine, urine flush water, hygiene wastewater, and simulated humidity condensate.[29]

Rector *et al.* (2006) tested a rotating hollow fiber membrane-aerated biofilm reactor (MABR) for wastewater processing; the rotation facilitated increased mass transfer and turbulent flow to optimize nitrification.[30] Habitation wastewater processing systems employing MABRs have been used for treating ISS urine, flush and humidity condensate, and Early Planetary Base (EPB) urine, flush water, hygiene wastewater, and laundry waste streams. Sevanthi *et al.* (2018) developed and optimized aerobic biological stabilization in MABRs that offers many advantages to current ISS wastewater processing: it eliminates hazardous pre-treat chemicals; eliminates volatile organic constituents; produces low pH effluent and produces less hazardous brine.[31] Bullard *et al.* (2023) have developed a Suspended Aerobic Membrane Bioreactor (SAMBR) for nutrient and water recovery from urine and gray wastewater streams. SAMBR is a hybrid technology that couples Biological Nitrogen Removal (BNR) and ultrafiltration tubular membranes. It uses active oxic and anoxic zones to tailor nitrogen conversion and removal, and ultrafiltration to generate a pathogen-free effluent that can be used for downstream production of potable water.[32]

Organic wastes generated by crew members (i.e., fecal and food wastes) are currently not recycled on the ISS, however, using this waste stream could result in significant amounts of recovered water and nutrients. Smith *et al.* (2022) developed an Anaerobic Membrane Bioreactor (AnMBR) that breaks down complex organic waste (i.e., fecal and food waste) using four sequential processes of anaerobic digestion (i.e., hydrolysis, acetogenesis, acidogenesis, and methanogenesis) to produce biogas and a nutrient-rich effluent.[33] Saetta *et al.* (2021) developed a flat-plate phototrophic membrane bioreactor (PMBR) that can treat high ammonia-nitrogen effluent from an upstream AnMBR. The PMBR allows algal biomass accumulation with high nutrient removal rates, nitrification of ammonia to nitrate, and production of a filtered permeate for downstream plant growth systems.[34] The Anaerobic Phototrophic Membrane Bioreactor (APMBR) treats the AnMBR effluent with the PMBR. Another bioreactor system under development for space exploration is a two-stage nitrification-anammox system for treating high strength nitrogen wastewater at Texas Tech and Pancopia.[35] These types of dual-stage reactors are developing capabilities to fully denitrify ammonia into nitrogen gas that could be used for atmospheric revitalization.

Table 1. BLiSS Technologies Required for Habitat Stages. *Each ECLS subsystem represents hybrid components utilizing physicochemical and bioregenerative components. A candidate hardware, rated for its current TRL, is presented for each category.*

Subsystem	Function	Hardware	TRL
Air Processor	• Provide clean air for crew • Recover condensate • Provide CO_2 for plants	• Air revitalization systems: CDRA, TCCS	9
Water Processor	• Provide clean water for crew • Provide clean water for plants	• WPA • Forward osmosis bag • Reverse osmosis	9 7 9
Urine Processor	• Mitigate urine & hygiene/laundry water • Recover resources (water/fertilizer/N_2)	• UPA / BPA (small systems) • SAMBR • Texas Tech MABR • MABR-PAX	9 5 5 3
Organic Processor	• Mitigate metabolic waste slurries (feces, food waste, vomit, etc) • Recover resources (water, fertilizer, CH_4/CO_2)	• APMBR • AnMBR	5 5
Trash Processor	• Mitigate trash and reduce volume of residue • Recover CO_2	• Heat Melt Compactor • OSCAR	8 6
Plant Production	• Produce food for crew • Revitalize air (O_2) • Further purify water	• Veggie and APH • OHALO • Eden ISS	9 5 7

VI. Assembling Candidate Technologies to Achieve M2M Objectives

The subsystems and their functions - processors of air, water, urine, organic waste, trash, and plant production needed for each of the BLiSS operations - are shown in Table 1. The corresponding hardware categories list current candidate technologies that exist in different stages of Technology Readiness Level (TRL). The hardware assigned to each functional category in Table 1 represents the list of technologies currently being traded and evaluated in the MCO program to perform critical functions within the BLiSS surface system architecture. Physicochemical air revitalization, water purification, and urine processing technologies are at TRL 9 due to their flight use in the ISS ECLSS. Whereas other technology platforms are being developed towards a sustainable Artemis X mission. Analysis of the biological water processors functions provides the ability to refine the ISS regenerative technologies as evolving ISS models towards a lunar surface system.[21-23] To achieve a BLiSS surface system architecture, a functional flow diagram was derived using these technologies and shown in Figure 5. Within this diagram, each unit and their corresponding function depict how critical inputs and outputs to the functions interact with each unit. For example, human wastewater from astronauts enters the bioreactor unit, along with hygiene and laundry wastewater and brine water, to be processed and produce nutrient/fertilizer and clean water. These units are then expanded from a functional role to a system architecture design with hardware testing. In the future as the units advance their TRL, verification and validation of input/output waste streams will be fully characterized and optimized for flight operations to enable a sustainable Artemis X mission.

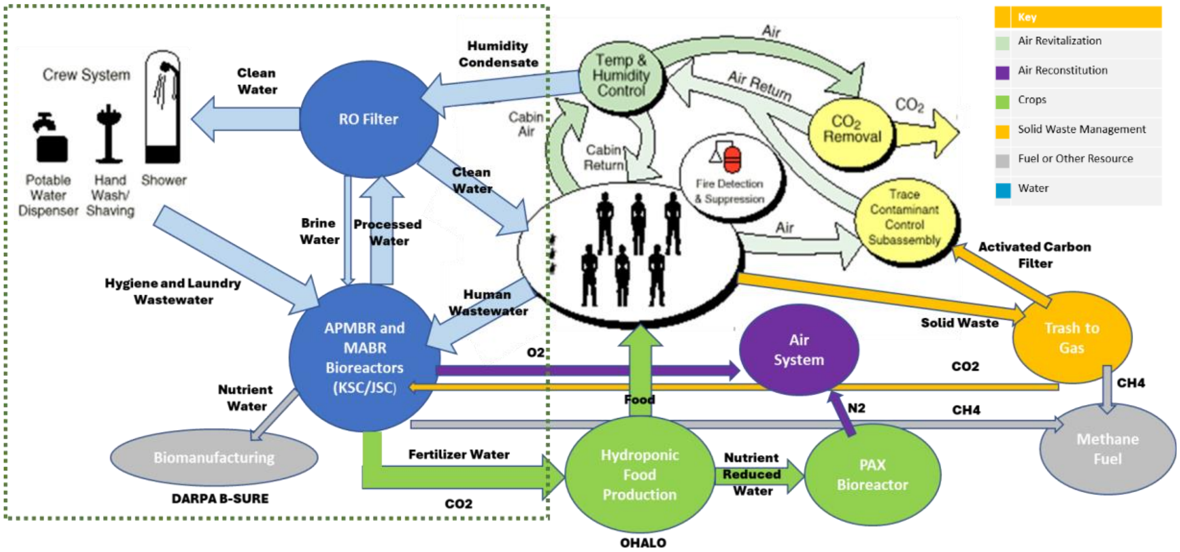

Figure 5. FY25 Testing of Candidate Technologies. *Studies of candidate APMBR and MABR reactors at KSC and JSC, respectively, show how these reactors can add useful inputs (i.e., O_2, CH_4, reclaimed hygiene and laundry water, fertilizer, and nutrient water) to the existing ISS ECLSS.*

Current studies evaluating APMBR and MABR bioreactors are generating data for determining how these novel candidate recycling technologies can contribute useful by-products (i.e., O_2, CH_4, reclaimed hygiene and laundry water, fertilizer, and nutrient water) for downstream use in the Sustainable and Mature Stages of habitat evolution. The current focus of the MCO portfolio is within the green dashed box within Figure 5. This initial data will be useful for evolution of the surface system BLiSS architecture, as well as for conducting trade and modeling studies for down-selecting, integrating, and mass balancing these waste recycling technologies that are currently in work at NASA and its partners.

VII. Conclusion

Bioregenerative life support systems can provide sustainable life support to human crews living in lunar and Martian surface habitats during long-term exploration missions. Human-rated demonstrations of BLiSS habitats carried out in Bios-3, CEEF, and the Lunar Palace 1 employed only basic solid and organic waste recycling systems. These demonstrations indicate that a large technology development gap exists in the implementation of BLiSS technologies for waste recycling. Closing this gap will require development and testing of technologies that recycle human organic wastes into resources that can be used as fertilizers and feedstocks that promote biomanufacturing in future surface systems. These waste recycling technologies, in turn, enable stable habitation capabilities when integrated into an evolving BLiSS architecture, employing both physicochemical and bioregenerative technologies, to support lunar missions described in NASA's M2M architecture. It is expected to take 6 years to further design, build, validate, and integrate these BLiSS recycling technologies with existing high TRL air revitalization, water processing, and food production life support technologies to support a fully sustainable Artemis X mission. The staged evolution approach as described, when implemented, culminates in the development of sustainable BLiSS for deployment in future lunar and Martian habitats.

Acknowledgments

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