Divergent Deployable Wastewater Treatment Facility

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NASA's Moon to Mars Campaign seeks to achieve a sustained Lunar presence as part of its strategy to enable crewed missions to Mars, an ambitious feat that will propel humanity into space further than ever before. Before a sustained presence on the Lunar surface is attained, an initial habitat solely focused on the essential survival elements (e.g. water reclamation) of the crew must be developed, studied, and optimized. At the Kennedy Space Center, a divergent deployable wastewater treatment facility (DDWTF) is currently under construction with plans to be integrated into the Integrated Lunar/Martian Analog Habitat (ILMAH) at the University of North Dakota (UND). The overall vision of the DDWTF is to process separate distinct astronaut wastewater streams (fecal, urine, hygiene/laundry) and convert them into value added products such as nutrient fertilizer and reusable water. The DDWTF houses a series of bioreactors and a vertical garden. These bioreactors – the Anaerobic Phototrophic Membrane Bioreactor (APMBR), Suspended Aerobic Membrane Bioreactor (SAMBR) and the Membrane Aerated Biological Reactor (MABR) – were built to collect and eliminate logistics wastewater through individual treatment processes. Individual processes are necessary for spaceflight when the astronaut population is small, and specific wastewater concentrations are high in solids, salts, or surfactants. The APMBR converts black wastewater streams (e.g. fecal) and generates a nutrient fertilizer effluent. The nutrient fertilizer will then be used hydroponically for plant growth located in the vertical garden. SAMBR processes the urine wastewater streams, while MABR processes gray wastewater streams (e.g. laundry/hygiene water). The objective of SAMBR and MABR are to regenerate water that can be further polished into potable water. Combining these bioreactors into a DDWTF is the first step towards developing a deployable, robust wastewater treatment module and water purification system for Lunar and Martian habitats.

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Acronyms and Nomenclature

AC = *Air Conditioning*
APMBR = *Anaerobic Phototrophic Membrane Bioreactor*
CHAPEA = *Crew Health and Performance Exploration Analog*
BLiSS = *Bioregenerative Life Support Systems*
CO_2 = *Carbon Dioxide*
DDWTF = *Divergent Deployable Wastewater Treatment Facility*
EC = *Electrical Conductivity*
EP = *Electrical Panel*
EPSCOR = *NASA Established Program to Stimulate Competitive Research*
ILMAH = *Integrated Lunar/Martian Analog Habitat*
LED = *Light Emitting Diode*
JSC = *Johnson Space Center*
KSC = *Kennedy Space Center*
M2M = *Moon to Mars*
MABR = *Membrane Aerated Biological Reactor*
MCO = *Mars Campaign Office*
MLE = *Modified Ludzack-Ettinger*
NASA = *National Aeronautics and Space Administration*
NASEM = *National Academies of Science, Engineering, and Medicine*
NFPA = *National Fire Protection Association*
NFT = *Nutrient Film Technique*
OSHA = *Occupational Safety and Health Administration*
pH = *Potential of Hydrogen*
RV = *Recreational Vehicle*
SAMBR = *Suspended Aerobic Membrane Bioreactor*
SSPF = *Space Science Processing Facility*
TDS = *Total Dissolved Solids*
TSS = *Total Suspended Solids*
TTU = *Texas Tech University*
UND = *University of North Dakota*
USF = *University of South Florida*

I. Introduction

A sustained human presence on the Lunar surface has been the prime focal point of the Artemis Campaign. The Moon will act as a true testbed for living on an extraterrestrial body in preparation for crewed Mars missions. As a strategy for enabling sustainable deep-space exploration, NASA has developed the Moon to Mars (M2M) Objectives document - a framework that outlines several key exploration goals along with recurring themes[1]. In this document, NASA indicates the need to develop surface habitats capable of maintaining crew life for long periods in deep space as an objective under the Transportation and Habitation goal TH-3[1]. It also identifies Maintainability and Reuse as a repeated theme throughout all Moon to Mars objectives[1]. This signifies technologies, when appropriate, should be designed to maximize reusability and/or recycling capabilities to promote self-reliance from Earth and prolonged sustainability[1]. The call for sustainable technologies aligns well with the National Academies of Science, Engineering, and Medicine (NASEM) *Thriving in Space: Ensuring the Future of Biological and Physical Sciences Research: A Decadal Survey for 2023-2032* as it emphasizes the recommendation that NASA should focus on Bioregenerative Life Support Systems (BLiSS) research to create and comprehend technologies that will handle waste, provide the needed commodities (e.g. food, water, and air) to the crew, and foster a sustainable space environment[2]. From this, it is understood that self-sufficient life support technologies within permanent surface habitats on Lunar and Martian terrain will be necessary to ensure crew safety, enable long-term expeditions, and ultimately achieve the goal of a sustained presence.

To build towards an Artemis permanent surface habitat, staged evolution will first focus on the essential survival commodities (air, food, water). Following our proposed notion of an evolving BLiSS architecture for surface habitats, an early variation of the habitat will implement both physiochemical and bioregenerative technologies to initiate the transition from short to long duration Artemis missions[3]. At this stage, food and air revitalization would continue to depend on resupply missions while closed-loop water reclamation and nutrient recovery via metabolic waste recycling are implemented[3]. Continued research and technology efforts on water recovery and metabolic waste management are imperative as it generates the necessary inputs (e.g. recycled water, nutrients) that support other life-support related technologies (e.g. plant growth systems) - helping progress the habitat to the mature/sustainable stage[3]. As such, creating a sustainable wastewater purification module for the initial habitat stage is the first crucial step.

Previous wastewater research at NASA's Kennedy Space Center (KSC) involved collaborations with university partners on a series of biological reactors to independently collect and treat wastewater streams (fecal, urine, laundry/hygiene) while recovering value-added commodities. These bioreactors – Anaerobic Phototrophic Membrane Bioreactor (APMBR), Suspended Aerobic Membrane Bioreactor (SAMBR), and Membrane Aerated Biological Reactor (MABR) were successfully studied in the laboratory setting demonstrating their capabilities to process divergent wastewater streams. APMBR was shown to effectively digest simulant material over a multi-year study converting the fecal/food waste into methane/carbon dioxide gas and a nutrient solution heavy with nitrogen, phosphorus, and potassium[4]. Whereas, SAMBR has been demonstrated to effectively treat salt-heavy urine simulant and real urine at the University of South Florida[5]. And the MABR system was demonstrated over a multi-year study at Texas Tech University demonstrating its capabilities to process hygiene water followed by reverse osmosis to generate reclaim and near potable water[6]. Each of these bioreactors were designed to fit within ISS EXPRESS rack dimensions[7], assuming habitation racks would use similar dimensions, since no habitation size requirements have been defined as of this publication. Each system was outfitted to consume less than 8 Amps of power at steady-state operation to minimize total power consumption.

To increase the bioreactors' individual Technology Readiness Levels (TRL), our team was directed by the Mars Campaign Office (MCO) to construct a mobile wastewater treatment facility to demonstrate the bioreactors' ability to process wastewater streams generated from pseudonauts in Johnson Space Center (JSC)'s Crew Health and Performance Exploration Analog (CHAPEA). Before integration into a CHAPEA Mission, NASA's ESDMD set requirements for mission integration by reaching TRL 5 through demonstration of the bioreactors' capabilities in a low-fidelity analog relative environment. Therefore, through a NASA Established Program to Stimulate Competitive Research (EPSCOR) grant to UND, NASA built a deployed a DDWTF to demonstrate each bioreactor's capabilities in a relative environment using real human metabolic waste. This paper outlines the DDWTF for its design, purpose, and capabilities prior to deployment and operation in a low-fidelity Lunar/Martian habitation system

II. Deployable Divergent Design

During the conceptual design phase of a bioregenerative water purification system, the critical determining factor was to assess whether the wastewater streams should be processed divergently or convergently. As the purpose of this research effort was to demonstrate the treatment of pseudonaut metabolic wastewater streams in a remote analog habitat, the low population size was the determining factor for selecting the wastewater treatment process. A small crew size of four to eight astronauts produces high concentrations of solids (total suspended, TSS) and salts (total dissolved, TDS) along with other chemical constituents from the wastewater streams (e.g ammonium from urine, surfactants from hygiene/laundry water) mainly because of the small volume of water[8]. This is evident on the International Space Station, and why the urine and fecal systems are separated onboard to process and/or dispose of waste accordingly[8]. For biological systems, terrestrial systems are usually convergent in either septic or sewar systems. Both approaches use large volume tanks to provide resonance time for solids to digest biologically. These systems are also designed as 'open environment' where processed water and sludge are returned to the environment and gas evolution is relatively ignored. These two reasons alone, using a terrestrial convergent approach is not feasible for a Lunar/Martian habitat. In addition, using a terrestrial convergent system for a small volume tank with high TSS/TDS concentrations would lead to an insufficient dilution – producing an overly potent liquid sludge that would be significantly more difficult to biologically process due to the low viscosity and high salinity. Therefore, diverting the liquid waste streams like those on ISS was more practical even though it requires multiple bioreactors.

Our proposed divergent treatment process biologically extracts essential elements from each wastewater stream within the bioreactors using different, specialized microbial consortia. This method offers the opportunity to fine-tune product water for specific end-use applications to close the water and element cycles. This approach reduces logistical resupply by eliminating human metabolic waste, purifies all water to have 100% retained/recycled water, and repurposes carbon, nitrogen, phosphorus, potassium, and calcium element cycles for fertilizer or biomanufacturing applications. A simple flow diagram depicting a closed divergent wastewater treatment process with the APMBR, SAMBR, and MABR is shown in Figure 1. Starting liquid waste streams are diverted based on chemical constituents and processing difficulty. Mostly pure water sources from Sabatier and humidity condensate can go directly to a commercial reverse osmosis water system for polishing. High carbon, low salt wastewater from laundry and hygiene operations are sent to the MABR system for processing, whereas low carbon, high salt urine is processed by SAMBR. MABR can also process urine in its COMANDR setup[14] and has been shown to trade better than SAMBR/MABR[15] in a bio-ECLSS system. And for high solids systems, the hybrid APMBR system[7] processes fecal and microbially digestible food waste.

To enable the design to be deployable, an 8.5 ft x 24 ft trailer was chosen as the housing. A trade study between a trailer, RV, and Conex was conducted based on cost, schedule, transportability, modifiability, complexity, employee work conditions, and risk. Key enabling functions of the trailer were designed into the housing to include an E-tracks system to provide safe hardware securing during transportation, a recirculating air conditioning (AC) unit, and a mini-slit for additional heating. The recirculating air conditioning unit allows for humidity and temperature control for plant growth and to meet OSHA operating requirements. The trailer was designed to use a 50-amp electrical panel box which provides sufficient power to all the subsystems while using a standard 50-amp RV cord/receptacle for easy transportation. The trailer has a standard 36-inch doorway and a full width loading ramp that can be used as an attachment and detachment point for an analog habitat – reducing complexity of the interface process. From this point onward, the mobile wastewater treatment facility was designated as the divergent deployable wastewater treatment facility (DDWTF). With the divergent wastewater processing method selected and designed, the subsequent decision centered on choosing a location that can host the subsystems while simultaneously be suitable for long distance transit and operator friendly. The location and layout of the DDWTF as well as the descriptions of the subsystems are discussed in the following section.

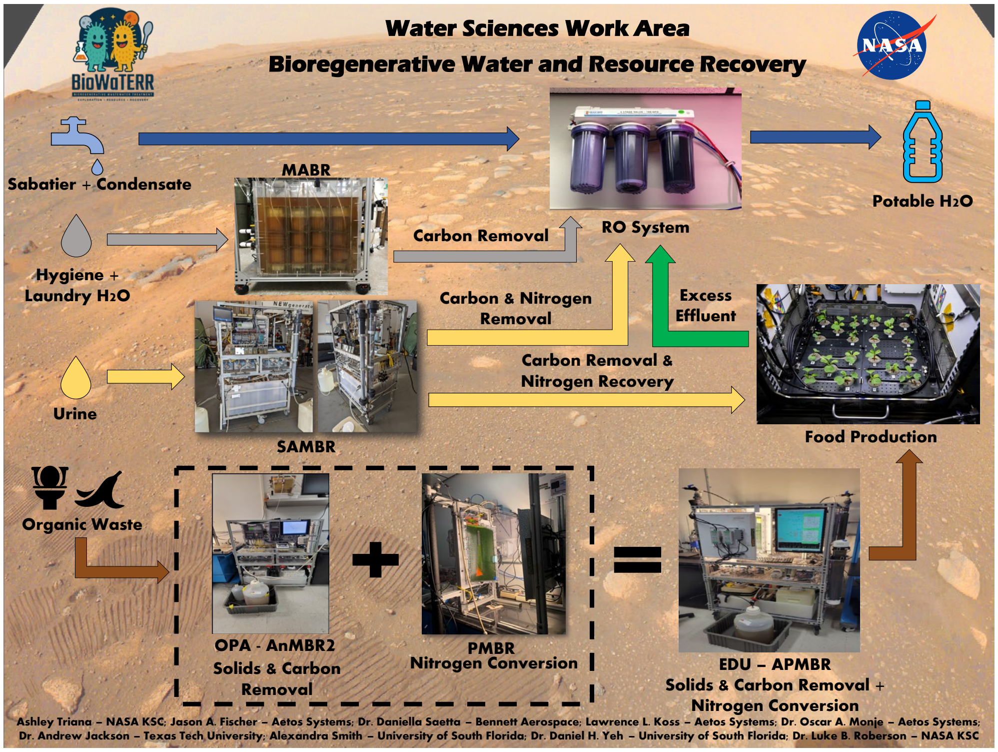

Figure 1. Schematic process overview of DDWTF.

III. DDWTF Location

In Florida, there are no well-established analog testbed sites where these bioreactors can integrate to fulfill the low-fidelity testbed demonstration requirement for CHAPEA entry. Therefore, the subsystems would have to travel across the nation for two separate missions - one to a low-fidelity testbed at the University of North Dakota's IMLAH and the other to CHAPEA at JSC.

The DDWTF location was envisioned to be a complimentary habitation module to the main astronaut habitat. The module would ideally connect the main habitat bathroom and kitchen to the DDWTF to enable the water to be collected, processed, and transferred back to the habitat and greenhouse for a fully recycled system. In the habitat, the DDWTF would be connected to power, water, air, and ventilation subsystems to share, process, and clean air and water commodities. However, to build a prototype system for deployable testing, the module was designed and constructed as an extension to a laboratory. Thus, the module followed NASA laboratory requirements to meet safety and mission assurance standards that met or exceeded NFPA and OSHA standards.

At KSC, the DDWTF was situated outside the Space Science Processing Facility (SSPF) due to having proximity with the team's primary work area as well as the facility's power, internet, and water source. An external 200-gallon tank was placed next to the trailer to hold liquid waste that was generated by subsystems in the trailer, since sewar connections were not readily available.

At UND, the DDWTF will be connected to UND's IMLAH facility as shown in Figure 2 outlined as a red box. Between DDWTF and IMLAH will be a bathroom that incorporates a urine diverting toilet. The commercial urine diverting toilet separates the urine going to SAMBR from the fecal going to APMBR. The bathroom also accounts for a small height difference between floors within the two housing units. At CHAPEA, the trailer would reside outside of building 220 at JSC and attach to the habitat's piping currently directed to the sewar.

Figure 2. Location of DDWTF at UND's IMLAH.
Red box is where the trailer will be located. Yellow box will be the bathroom.

IV. DDWTF Layout and Subsystems

The trailer is intended to be a mobile wastewater treatment facility to elevate the bioreactors' capabilities at TRL 4 in a relative environment to achieve TRL 5 using real human metabolic waste. The housing, being a laboratory, was required to meet OSHA and NASA requirements for operating biological and chemical operations. The heart of the DDWTF focuses on three bioreactors (APMBR, MABR, SAMBR) to process different wastewater streams. Each wastewater permeate then travels to a vertical garden, water polisher, or holding tanks (influent and effluent) for other applications, testing, or disposal. Auxiliary systems such as an oxygen concentrator, a CO_2 K-Bottle, a computer system, and a sink with an eyewash are parts of the structure to enable the bioreactor operations and operator safety. Figure 3 depicts a two-dimensional layout of the DDWTF.

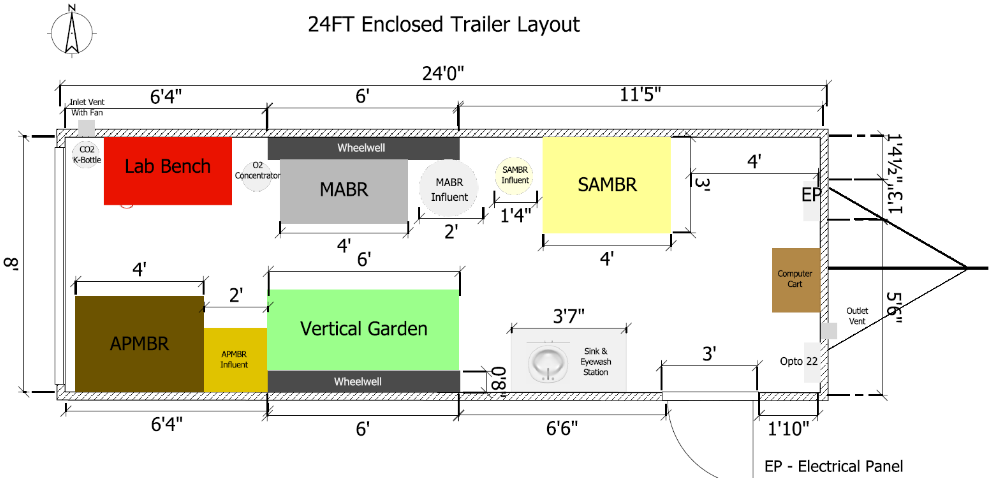

Figure 3. **DDWTF Layout**

Trailer Fundamentals

Because DDWTF is part of the TRL test plan, the trailer was adapted to meet laboratory requirements, because people will be working inside the trailer both unattached at KSC and attached to IMLAH. To meet NASA safety requirements, the team installed safety equipment such as a sink, eyewash, offline gas detection system, and an online environmental monitoring system. Sink and eyewash are OSHA requirements when handling chemical and BSL 1 organisms. The environmental monitoring system employs an OPTO 22 Groov hardware to test air concentrations for an oxygen deficient environment, presence of ammonia and carbon monoxide, temperature, and humidity. OPTO 22 regulates the atmospheric environment by engaging an internal recirculating air conditioner with heating tape and a split mini-AC for outside air makeup. Vent fans were installed in case excess gas produced by the bioreactors built up in the trailer or in the rare case a gas bottle vented.

APMBR

Following our previous research, we successfully demonstrated APMBR's capabilities to treat simulated fecal and food waste and convert that into a nutrient fertilizer for crop production[8,9]. Our collaborators at the University of South Florida (USF) also demonstrated its capability to process real canine fecal waste and grow crops[6]. The next step to advance this technology is to demonstrate the reactor's ability to process real human fecal waste at IMLAH. The APMBR was moved and installed into DDWTF. The system is designed to process 2.4 L of fecal and food waste per day for a crew of four, as determined by NASA's M2M program[11].

MABR

Research published by Andrew Jackson at Texas Tech University (TTU), funded under a NASA grant, demonstrated that their membrane assisted bioreactor (MABR) can clean hygiene water and produce clean water[9]. Professor Jackson's team built and shipped a MABR to KSC for incorporation to the DDTWF. The system was outfitted on a 1.25" 80/20 frame and upgraded to autonomously operate on OPTO 22 control system. An oxygen concentrator was attached to increase the kinetics of the aerobic bacteria rather than using room air. Concentrated oxygen flows through a set of mass flow controllers to ensure that 50 mL/min is sent to the membrane modules. The oxygen concentrator was chosen by NASA safety over a standard K-bottle due to flammability and safety hazard mitigation. The system is designed to process 50 L of hygiene and laundry water per day for a crew of four, as determined by NASA's M2M program[11].

SAMBR

Previous work at KSC and USF demonstrated and patented a process for using a suspended aerobic membrane bioreactor (SAMBR)[5,8]. This system uses a Modified Ludzack-Ettinger (MLE) approach to treat high-salt urine wastewater within a 120 L bioreactor. The system was upgraded with a 1.25" 80/20 frame and OPTO 22 control system to match the APMBR and MABR systems for a single operating system. The system is designed to process 9 L of urine plus flush water per day for a crew of four, as determined by NASA's M2M program[11].

Vertical Garden

The Vertical Garden testbed in DDWTF was designed as a food production demonstration fed by fertilizers from effluents produced by APMBR, MABR, and SAMBR. Bioreactor effluents from APMBR generated at ~2.5 L/day will be used as nutrient solutions and diluted by purified water from MABR and SAMBR effluents. The nutrient concentration and efficacy for crop production will be tested in IMLAH using simulant and real human metabolic waste as feedstock. Crop productivity of plants grown using effluent-generated nutrient solutions will be assessed by comparison to plants grown in a standard hydroponic nutrient solution in the same environmental conditions. The goal of this work is to validate the nominal operation of the Vertical Garden system in DDWTF and to demonstrate plant growth using nutrient solutions derived from bioreactor permeates in ILMAH.

The Vertical Garden consists of a three-level growing rack with three independent recirculating hydroponic nutrient solution tanks (Figure 4). Each nutrient tank will supply one hydroponic nutrient film technique (NFT) channel per level. Each tray in each level consists of a 4 inch-long CropKing hydroponic NFT channel that is drained to a 30 L nutrient tank. Nutrient solution is recirculated using Little Giant pumps. Lighting in each level is provided by two 2' x 4' Mars Hydro dimming TSL 2000 LED fixtures. Each nutrient tank will be equipped with a pH, an EC meter, and a pump for pH control. Sensors will be interfaced with the DDWTF OPTO 22 system, that will allow photoperiod control and data monitoring.

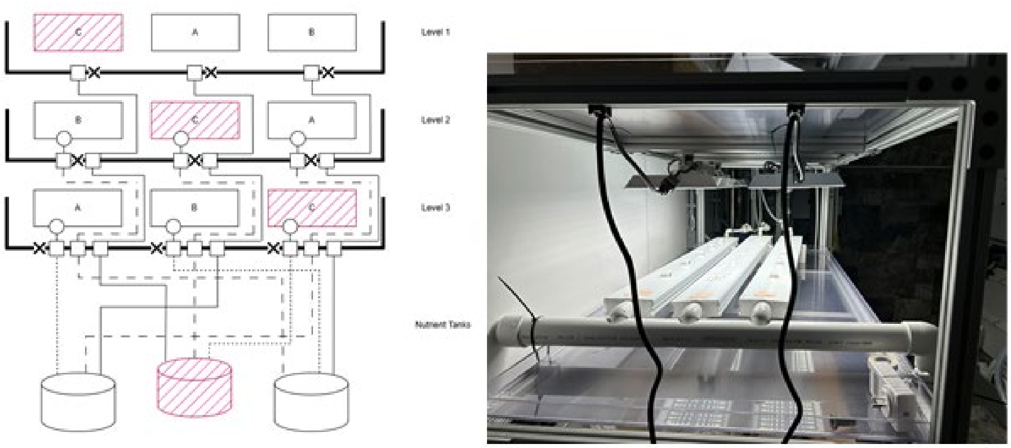

Figure 4. **Vertical Garden within DDWTF. (Left) Schematic of NFT setup. (Right) Single level of three trays illuminated by two LED fixtures.**

V. Deployable Operations

The DDWTF operations begin with humans. The toilet interface for the divergent system employs a commercial urine diverting toilet called EcoFlush from Ecovita. The toilet sends the urine plus flush water in the front of the toilet bowl down a small tube to SAMBR, while the fecal and flush water get sent via a larger tube to APMBR. The bioreactors operate independently and autonomously to process their waste streams to produce effluent products. Biogas produced from the reactors is measured and vented outside DDWTF. Eventually the methane in the APMBR biogas will be collected and used for fuel, while the carbon dioxide will be sent to the SAMBR carbonation column to control pH. This will help close the element cycle for lunar operations. Nutrient effluent from the APMBR is sent to the vertical garden. Nutrient concentrations monitored by EC and pH sensors determine if APMBR effluent should be diluted with clean MABR effluent. If unnecessary, APMBR effluent will be used as direct nutrient solutions to grow crops; however, if the EC/pH data is too high as seen with other previous experiments[16], MABR effluent will be used to control nutrient concentrations.

At KSC, checkout testing operations were performed in a relatively stable environment. Weather conditions during winter months were pleasant. However, this isn't expected on the Moon or in North Dakota[17]. To maintain a moderate habitation temperature within ILMAH and DDWTF, the housing will be connected to share internal temperature. Thermal insulation will be wrapped around the exterior of the trailer to help moderate temperature. And the mini-split and heating recirculation tape will help keep temperatures within the trailer operable for humans and microbes. Because of the extreme temperatures at UND, DDWTF will be operated between April and October from 2026 through 2028, giving relatively six months of operations and 6 months of dormancy and three test periods. This will help avoid severe snow weather conditions for operators.

VI. Challenges and Lessons Learned

Throughout the outfitting process of the trailer, the team encountered unforeseen obstacles that required innovative problem-solving and/or collaboration to resolve. Challenges such as electrical safety, HVAC, compressed gasses in small areas, and oxygen concentrators were all safety concerns the team addressed as DDWTF was brought to life.

VII. Conclusions

To build a divergent wastewater processing system for the lunar outpost, the team assembled a series of previously validated bioreactors to process different divergent waste streams in a relative environment analog mission. The bioreactors were consolidated into a single 24 ft trailer and outfitted with complete autonomous operating and safety systems. Integration into the UND ILMAH is anticipated to begin April 2026 with testing completed in September 2028. This relative environment testing will help the team understand the real vs simulant wastewater conversion, system operation and training, and eventual transition plans to higher fidelity testbed at CHAPEA.

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