Evaluation of an Aeration Module for Microbial Environmental Control Life Support System (mECLSS) Integration with ECLSS

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Space habitats utilize Environmental Control Life Support Systems (ECLSS) to produce continuous supplies of potable water from waste streams. The approach to ECLSS of the last two decades on the International Space Station (ISS) has been to inactivate microbial populations with chemical or radiative biocides to enable physical-chemical processes to convert wastewaters to water that meets potable requirements. This approach enables high water closure rates, but creates operational challenges: biofilm blockages, odors, incomplete carbon cycle closure, and hazardous brines. Metabolic emissions from the human crew contain reduced carbon and nitrogen compounds that serve as substrate (food) for bacteria. Despite biocidal inactivation strategies, unmanaged aqueous bacterial populations remain active at niche locations in the ECLSS subsystems. The only managed biological processes on ISS are the experimental plant growth chambers which provide the optimal environments for photosynthetic reactions but are not integrated into ECLSS. This paper provides technical background on an engineering aeration technology to support beneficial microbial respiration in habitat wastewaters. An engineered technology to control and utilize microbial growth is defined as a microbial Environmental Control Life Support System (mECLSS). A potential location for introducing mECLSS with minimal engineering configuration changes is as far upstream as possible to lower the biofilm forming potential of microbial substrates in downstream segments. An aeration module (AM) using gas-permeable tubes would provide adequate dissolved oxygen to biologically stabilize the organic load in condensate prior to physical-chemical processes. The AM would contribute to future ECLSS by preventing uncontrolled biofilms and by increasing the capacity of the current WRS to process condensate when cabin air concentrations of VOCs are elevated. The AM would also provide a critical first step in adding a bioregenerative component to the ISS ECLSS air and water systems.

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Nomenclature

APH	=	advanced plant habitat
aq	=	aqueous
BOD	=	biochemical oxygen demand
CCAA	=	Common Cabin Air Assemblies
CWC-I	=	contingency water container, iodine filled
ECLSS	=	environmental control and life support systems
EMU	=	extravehicular mobility unit
hECLSS	=	human environmental control and life support system
HC	=	humidity condensate
ISS	=	International Space Station
K_H	=	Henry's Law Constant
LEO	=	low Earth orbit
mECLSS	=	microbial environmental control and life support system
MF	=	multifiltration
MLS	=	mostly liquid separator
pECLSS	=	plant environmental control and life support system
SOA	=	state-of-the-art
TCCS	=	trace contaminant control system
TIC	=	total inorganic carbon
TOC	=	total organic carbon
TRL	=	technology readiness level
TTU	=	Texas Tech University
VOC	=	volatile organic compound
WPA	=	water processor assembly
WRS	=	water recovery system

I. Introduction

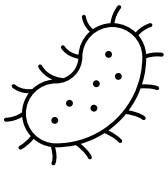
SPACE habitats utilize Environmental Control Life Support Systems (ECLSS) to produce potable water from human waste streams. During the 24 years of continuous human habitation within closed habitat of the International Space Station (ISS), the ECLS systems in the US and Russian segments have successfully supported the lives of more than 270 humans from throughout the world. Their microbial crewmates have received less fanfare, but have played a role, often in the form of causing problems, such as plugging up flow paths. The on-orbit approach to ECLSS of the last two decades on ISS has been to inactivate and control microbial populations with biocides and filters to enable physical-chemical processes to convert biologically active wastewaters to deionized water that meets stringent requirements for potable water and Extravehicular Mobility Units (EMUs) water. This approach enables high water closure rates in the challenging micro-gravity environment, but creates operational challenges including chemical resupply, biofilm blockages, odors, incomplete carbon cycle closure, and hazardous brines. Despite biocidal inactivation strategies, unmanaged bacterial populations remain active at niches in ECLSS subsystems.

A critical requirement of human life support in space is focused on supporting the healthy and continuous respiration by the crew as their human cells oxidize organic compounds with oxygen and emit carbon dioxide and water. One key biochemical process that is not managed on ISS is microbial respiration, which is very similar to human respiration for aerobic bacteria. On Earth, bacteria play a key role in the carbon cycle, with about 110 Gton-C of carbon converted to carbon dioxide by soil bacteria to match the 110 Gton-C of carbon produced by photosynthesis each year.[1] This global balance between respiration and photosynthesis is why our yards don't overflow with grass clippings. In the case of ISS, although we have introduced and managed photosynthesis reactions in plant chambers, we have yet to introduce and manage naturally occurring microbial respiration for beneficial purposes. On Earth, most of the microbial respiration and oxidation of organics to carbon dioxide occurs in soils, which are absent on ISS. There are 10^8 to 10^9 bacteria per gram of soil actively at work breaking down organics and producing carbon dioxide.[2] Another difference between the global carbon cycle and ISS is that the organics circulating on ISS are principally from metabolic emissions by the crew and off-gassing from surfaces, instead of from photosynthesis. Plants grown in

plant chambers do emit some volatile organic compounds (VOCs) as well. For human metabolism, the organic compound (electron donor) is of course, food. The food for the human crew's metabolism on ISS is mainly resupplied in packages rather than grown within the habitat. Introducing, managing, and integrating microbial degradation of organics is a critical step in closing the carbon cycle in habitats.

There is great interest in transitioning from the successful regenerative air and water systems on ISS to bioregenerative processes that enable more complete, Earth-independent, sustainable closure of the water, carbon, and nitrogen cycles. This "biological gap" is particularly true for future surface missions of long duration. In bioregenerative processes, the respiration of humans and microbes are merged with the photosynthetic processes of plant growth and food production.[3,4] The only managed non-human biological processes on ISS are the Veggie and the advanced plant habitat (APH) which provide the optimal environments for plant growth and photo-synthetic reactions.[5] This paper serves as a roadmap by proposing the first, simplest, and least disruptive step in moving from our current state-of-the-art (SOA), Point A (regenerative ECLSS with limited plant growth) to Point B (bioregenerative ECLSS). Point A is our current location on the road map, with human ECLSS (hECLSS) and plant ECLSS (pECLSS) already implemented on ISS. We note the current SOA ISS hECLSS has niches of unmanaged microbial respiration. Our destination, Point B, occurs when human and microbial environmental control and life support systems (mECLSS) are integrated in new symbiotic ways in a space habitat. The goal of this paper is to provide technical background on the importance of engineering aeration technologies to manage microbial respiration to support naturally occurring, healthy, and beneficial biofilms in habitat wastewaters. We will use the ISS Habitat as a well-established starting reference with more than two decades of successful on-orbit human-centric ECLSS (Table 1).

Table 1. Framework of Main Metabolic Processes and Supporting Technologies within Space Habitats.

ISS ECLSS			
Category	***hECLSS***	***mECLSS***	***pECLSS***
Life Supported	Human 	Microbial 	Plant 
Metabolism	Respiration	Respiration	Photosynthesis
Reactants	$C_6H_{12}O_6 + O_2$	$C_2H_6O + O_2$	$6\ CO_2 + 6\ H_2O +$ photons
Products	$6\ CO_2 + 6\ H_2O +$ energy	$2\ CO_2 + 3\ H_2O +$ energy	$C_6H_{12}O_6 + 6\ O_2$
TRL of ECLSS	9	4	9

Note: Glucose, $C_6H_{12}O_6$, is used as the human substrate and Ethanol, C_2H_6O, is used as microbial substrate.

II. Unmanaged Microbial Populations on ISS

Microbial niches are found throughout the ISS habitat. Microbes are ubiquitous in the habitat, being found and identified in urine, fecal matter, humidity condensate, WPA Wastewater, potable water,[10,20] and of course on and within the bodies of the crew where they outnumber human cells (human biome).[6] The success of bacteria to populate niches is partly due to their capability for exponential growth, their small size (~ 1 micron with a typical mass 10^{-12} gram per cell) and associated small requirements for food, oxygen, and nutrients.[7] Their small size creates a large

surface area of cell membrane on the order of 12 m^2/gram to support the rapid diffusion of metabolic reactants and products.[8] If we assume a typical organic carbon mass per bacterial cell of $1.5 \cdot 10^{-10}$ gram carbon/cell[8] we can calculate how many bacterial cells would result from the complete conversion of 3 mg/L of TOC to bacterial cells. The corresponding number of bacteria cells would be $2 \cdot 10^7$ cells/mL (typically measured analytically as $2 \cdot 10^7$ cfu/mL). Hence, relative to the water quality of waste streams, bacteria don't have large mass requirements for organic carbon and nutrients in order to survive. For the 50 cfu/mL potable water limit on coliforms,[9] those 50 bacterial cells per mL would represent an equivalent TOC concentration of 0.0074 ppb TOC. Hence, the use of biocides is required to meet the potable water requirement of 50 cfu/mL for the allowable TOC of 3 mg/L in potable water. The point here is that wherever we have small amounts of organic carbon and traces amount of nutrients, we will find a microbial population. In addition, the small dimensions of bacteria have some advantages in designing their life support requirements.

This paper proposes utilizing the microbial conversion of biodegradable TOC (substrate) to stable inorganic carbon (TIC) near the upstream source of the waste stream. As will be explained in the following sections, the conversion of TOC to TIC typically happens at the downstream end of the legacy ISS treatment train instead of the upstream end near the source of the waste stream. The upstream microbial transformation of TOC to TIC would biologically stabilize the waste for downstream physico-chemical processes by eliminating the food to support microbial growth. Providing aeration to support healthy, microbial populations in specified upstream locations would provide a new bioregenerative component to the traditional waste treatment system in space habitats. Aeration combined with an attachment surface for bacteria ("bioaeration") to form a physically stable and healthy biofilm would be a critical part of managing the microbial population to provide stabilization of the biodegradable TOC in the habitat waste streams while preventing the biofilm forming potential in downstream conduits and tanks.

ISS locations of particular interest in terms of microbiological activity and substrate supplies are the upstream regions of the WPA (Figure 1), starting at the cabin condensing heat exchangers CCAAs, where liquid water forms, flows through fan separators, and the associated conduits that carry the condensate to mix with urine distillate and enter the WPA wastewater tank. It is in the bellows tank that we find a well-established and naturally occurring microbial population (biofilm).[10, 11] We can view this as both a problem and a solution, a problem which hints at its own solution. The unmanaged microbial population indicates that this is a good location to consider a microbial environmental control and life support system (mECLSS) to promote the health of the microbes for beneficial purposes. The bacteria in the current system have insufficient oxygen relative to the food supply, so they are in a state of suffocation, unable to oxidize food for energy, resulting in death and detachment. Bacteria acquire their oxygen from the water phase in the WPA, in which oxygen molecules are poorly soluble due to their non-polar nature. To implement an engineered mECLSS, there would be no required addition of bacteria to the system, as the bacteria are already in the system, they just need an optimal supply of oxygen and a secure attachment surface, unlike the metal bellows surfaces that are isolated from the cabin air.

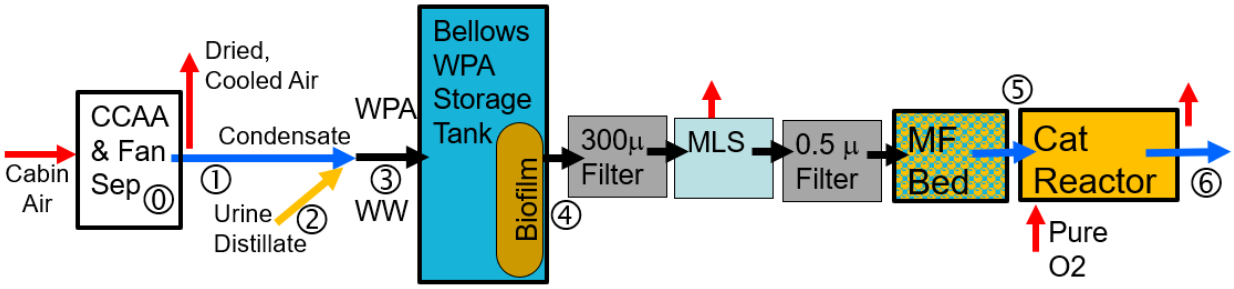


Figure 1. Current ISS Water Processing Assembly. Numbers in circles will be locations referred to in the text.

With a small additional source of oxygen (cabin air), we could convert all the problematic polar VOCs (that routinely breakthrough the WPA's MF beds[11]) to carbon dioxide and a small amount of microbial bioproducts, which are of high molecular weight and removable by activated carbon. The mass of oxygen required by bacteria to completely oxidize organics is known as the biochemical oxygen demand (BOD) and has units of mg-O_2(aq)/L. Some small number of suspended bacterial cells would also have to be managed, but the ISS system already has extensive filtration downstream of the WPA wastewater tank to handle the sloughed bacteria from the unmanaged biofilm within the bellows tank. Without the supply of air, the unmanaged microbial population converts only a fraction of the polar

organic compounds (e.g. ethanol) to carbon dioxide. For example, ethanol routinely flows into and out of the MF beds and into the Cat Reactor (Figure 1, Location 5) where it is oxidized by a high temperature catalytic process using pure oxygen.[12,11]

Figure 2 shows the estimated long-term average reductions in the ten most abundant VOCs by the current unmanaged biofilm within the WPA wastewater tank.[14] The influent is at Location 2 in Figure 1 and the effluent is at Location 3. The top of each vertical line in Figure 2 represents the influent concentration, and the bottom of each vertical line represents the effluent concentration (on the y-axis). The conversion of each organic compounds varies but is typically greater than 50% conversion. Bacteria are micro-catalysts, capable of oxidizing organic compounds at room temperature, without the need for the elevated temperatures, pressures, and pure oxygen conditions within the Cat Reactor. Most conveniently, bacteria thrive on the main metabolic emissions (compounds shown in Figure 2) that humans and even materials emit to the cabin air phase, which are then partitioned into the condensed water phase.

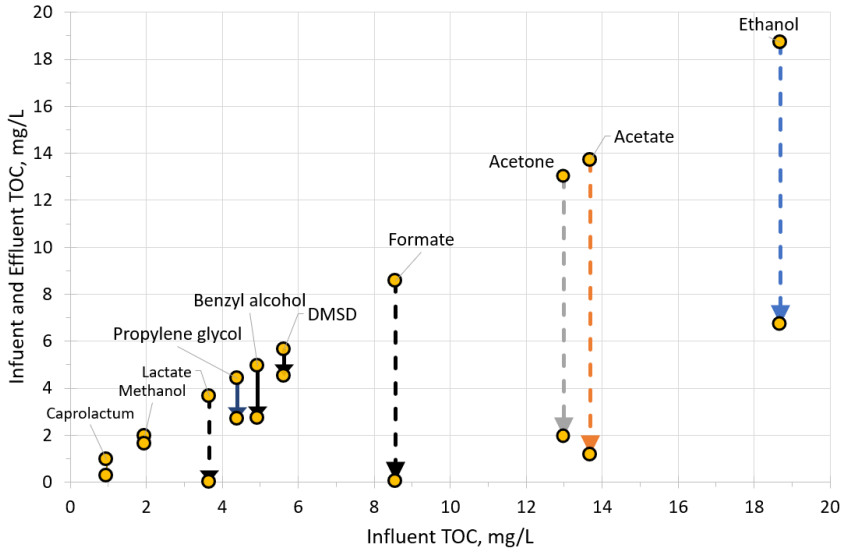


Figure 2. Averaged Concentrations of top ten organics' TOC in ISS WPA Wastewater Tank's Influent and Effluent. *Long-term averages, Urine Distillate contributions to influent estimated from ground testing data*.[14]

Due to the low organic loading of small organic molecules in condensate, this waste stream is a good potential location to introduce a mECLSS on ISS or in most habitats, as it requires small amounts of oxygen relative to the other waste streams (urine and fecal matter). In a later section, we will calculate how much oxygen is needed to completely oxidize ethanol in the condensate. The biochemical oxygen demand (BOD) required to oxidize organics and reduced nitrogen species in condensate is on the order of 0.37 g-O_2(aq)/L compared to 30.3 g-O_2(aq)/L in urine.[13] The small organics in the WPA wastewater cause the formation of a sustained biofilm within the WPA wastewater tank and downstream conduits.[14] The 300-micron filter in Figure 1 (downstream of Location 4) was added after the discovery of the biofilm in the WPA tank.

In this paper we focus on humidity condensate (Figure 1 Location 1) as the simplest and least disruptive location to introduce managed microbial respiration as far upstream as possible in the heritage ISS WRS treatment train. By focusing on condensate, which is collected daily, more opportunities are available to isolate and store condensate to introduce and manage the bacterial population for the first time in microgravity. This location offers samples collection ports, which are not available for urine distillate. Also, a contingency water container (CWC) could be filled with condensate and then aerated and monitored without disturbing the WRS operations for a flight demonstration. Collecting a sample or stream of urine distillate is currently not available in the current plumbing configuration of the ISS.[14]

III. Managed Microbial Populations: Aeration Modules treating Space Habitat Waste Streams

A. Evaluation of Aeration Modules treating Space Habitat Waste Streams

Details of the aeration modules that support microbial growth for the stabilization and treatment of simulated humidity condensate have been designed and ground tested for operational periods of years.[15,16,17] When a waste stream with biodegradable constituents flows through an aeration module, a naturally occurring microbial population establishes itself on the walls of the aeration tubes. An AM with a managed microbial population is typically termed a membrane aerated biological reactor (MABR). A range of MABRs were operated with a variety of mixed and separate simulated space habitat waste streams including urine, humidity condensate, hygiene, and laundry. The MABRs tested utilized gas permeable membranes (semi-permeable non-porous silicone tubes with 0.49 cm outer diameter and 0.115 cm wall thickness.[17] Silicone membranes can be operated at high gas pressures without bubbles forming. The ends of each tube are open to gas plenums to provide air in and air out to the cabin (Figure 3).

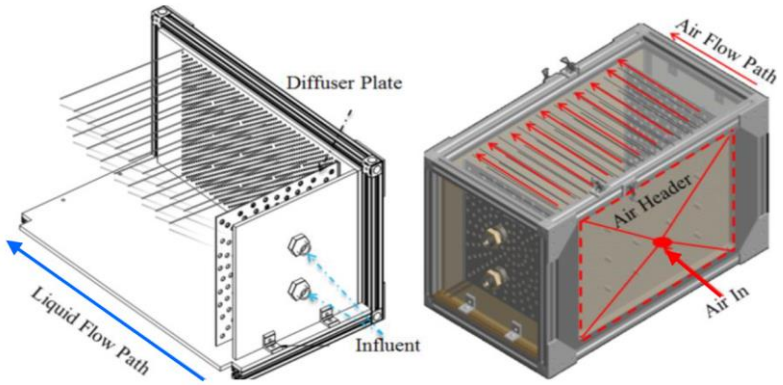


Figure 3. Rectangular Aeration Module for Treatment of Habitation Waste Streams.[18]

The tubes provide microgravity compatible aeration to waste streams without the formation of bubbles. The outer wall of each tube supports an attached microbial population (biofilm). Oxygen is provided to the base of the biofilm by flowing oxygen or air through the lumen of each tube. This provides co-directional mass transfer in which dissolved oxygen, O_2(aq), diffuses through the biofilm from the exterior tube wall towards the bulk wastewater liquid phase and the substrates (e.g. organic compounds) diffuse from the bulk liquid to the base of the biofilm which adheres to the exterior tube wall. In addition, other gas species produced within the biofilm, such as carbon dioxide, diffuse through the biofilm to the lumen, where they enter the gas phase and transfer back into the cabin air. The bioreactors provide a significant attachment surface for bacteria and a supply of oxygen by providing an aerated biofilm surface area of 100 m^2 per m^3 of reactor volume, enabling dissolved oxygen concentrations to be aerobic (typical range 8 to 22 mg-O_2(aq)/L) in the bulk liquid.[15]

Figure 4a shows an idealized membrane aerated biofilm, in which the flux of the electron donor (ethanol, C_2H_6O) is from the bulk liquid into the biofilm and the electron acceptor (dissolved oxygen) from the lumen is in the direction from the base of the biofilm towards the bulk liquid. This bidirectional flux of reactants promotes a stable biofilm with a strong affinity to the oxygenated membrane surface of the tubes. Figure 4b, shows a notional image of an unaerated biofilm, such as would be expected in the current WPA wastewater tank in Figure 1. Here the only source of oxygen is from the bulk liquid, and this results in a dying layer of bacteria at the base and interiors of the biofilm due to oxygen limitations in both supply and transport to and throughout the biofilm. Hence, it is prone to sloughing with the shed biofilm flowing downstream. In the healthy, aerated biofilm, sloughing of dead cells is minimized.

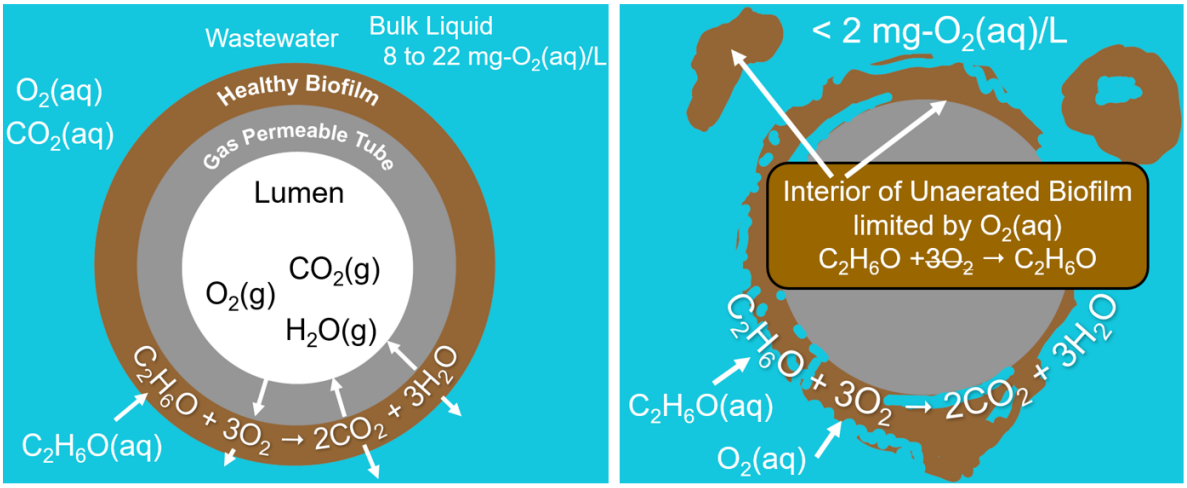


Figure 4. a) Idealized Biofilm in an MABR and b) Notional Biofilm without External Aeration (Air Lumen removed) representative of WPA Storage Tank.

Based on the long-term ground testing data of MABRs, the differences in module volume sizing and operational issues for the different waste streams can be estimated. The bioreactor for the humidity condensate reactor would be much smaller than a urine bioreactor. The condensate MABR would require 1 to 3 days of retention time versus about 25 days for a urine MABR.[15] There are no issues with free ammonia inhibition of the bacterial respiration in the HC reactor, for the urine if the pH goes above 8 or if the pH goes too low nitrous acid inhibits the microbial respiration, which requires intervention with acid of base addition. The main challenges of urine MABRs relative to condensate MABRs is the very high concentrations of reduced carbon and nitrogen and their associated high oxygen demand (>20 grams of oxygen required per liter), compared to condensate's oxygen demand of <300 mg per liter). Urine also has significantly higher salinity than condensate. Startup of the microbial population is guaranteed for condensate MABRs, as demonstrated by the biofilm in the WPA system and by ground testing,[15] whereas establishment of a urine MABR takes about 3 weeks and there is a need to control pH within a specific range during startup.

B. Ground Testing of Aeration Modules to Treat Simulated Humidity Condensate

The first aeration module to treat a simulated humidity condensate stream based on ISS condensate water quality was built and tested at TTU in 2018. It was challenged with a humidity condensate ersatz with very high organic loading of 430 mg-TOC/L, which was representative of earlier air revitalization systems.[19] This high concentration of TOC compares to three samples of condensate collected and returned from ISS in 2023 that had an average of 76 mg-TOC/L coming mainly from ethanol (average concentration of 56 mg-ethanol/L).[20] The small-scale aeration module used an aquarium pump to flow ambient lab air at 1 liter per minute through lumens of silicone tubes immersed in the HC, with the bacteria growing on the exterior walls of the tubes in contact with the condensate. Oxygen permeated the tubes from the lumen side into the biofilm and liquid condensate, and carbon dioxide permeated the tube wall from the biofilm into the lumen and into the condensate. For a 10-day retention time, the effluent TOC was less than 40 mg/L. This early, simple aeration module was not optimized in terms of surface area of tubes per volume and gas-liquid transfer.

A full-scale aeration module was tested to measure the impact of replacing a condensate storage tank with an aerated tank.[21] The AM treated simulated condensate that had influent TOC of 207 to 270 mg/L representing a crew size from 2 to 15 crew members (condensate flowrates of 3.9 to 30 liters per day). The operation of the reactor was evaluated over 7 months. The reactor treated almost 3,000 L (1,500 crew-days) of HC waste stream over 7 months of operation. The average pH of the reactor across all test points was in the range of 5.6 to 6.1. Oxygen was supplied as pure oxygen during this test. The system was able to reliably operate with high efficiency, low oxygen consumption, and no maintenance.

Recent ground testing of an MABR and reverse osmosis (RO) system to recover water from humidity condensate has been completed.[16] The system was run for over 200 days and treated 1,600 liters of simulated ISS humidity condensate and a downstream RO membrane process produced a total volume of permeate of 1,100 L of water for 170 days representing a crew of 4 humans. The successful operations of the RO downstream of the MABR provides evidence on the ability of MABRs to prevent biofilm growth in downstream conduits and physical-chemical processes.

C. mECLSS removal of problematic VOCs such as Ethanol

Within the ISS habitat, an interesting relationship exists between the gas phase concentrations of polar VOCs and their associated aqueous concentrations in condensate, which is processed by the WRS WPA. The safe maximum allowable concentrations (SMACs) in the cabin atmosphere of many organic compounds (e.g. alcohols) are orders of magnitude greater than the capacity of the WRS to remove the aqueous concentration associated with the gas-phase SMAC concentration. Allowable cabin air concentrations of VOCs is limited by the current WPA's capacity to remove polar VOCs.[20,22] As Jay Perry noted in his landmark manuscript, "The individual contaminant atmospheric concentrations that can result in condensate loading at the water processors design level are well below their respective SMACs."[22]

One example of the relationship between allowable gas-phase and liquid-phase concentrations is the polar VOC, ethanol. The 180-day SMAC for ethanol is 2000 mg/m^3 in the cabin air, so although this air concentration is safe to crew, the actual engineering limitation is on the order of 5 mg/m^3 because air concentrations above this amount can overwhelm the removal capacity of the water recovery system.[20,22] The 5 mg/m^3 ethanol gas-phase concentration results in an aqueous concentration of 103 mg/L in the condensate. The basis for this and other gas-liquid partitioning calculations is included in a later section. Polar VOCs such as ethanol "are difficult to remove from water" because they lack an affinity for both activated carbon and ion exchange resins.[22] Yet bacteria readily use ethanol and other small VOCs for their electron donor (food) as evidenced by the microbial community (biofilm) in the WPA wastewater tank (the small molecules are easily diffused through their cell membranes). On-orbit evidence of the naturally occurring microbial transformations of VOCs within the WPA tank were demonstrated by the data in Figure 2, which is based on measured water quality of returned WPA wastewater samples from ISS.[14] For example, the average TOC concentration of ethanol in the influent to the WPA tank was 18 mg-TOC/L, whereas the tank's effluent ethanol concentration was 6 mg-TOC/L.

A simple, controlled experiment was conducted to simulate the microbial respiration process and consumption of dissolved oxygen for a typical organic loading within the ISS WPA bellows tank, which is assumed closed to the cabin atmosphere and lacking aeration. To the authors knowledge, the dissolved oxygen concentration has never been measured in any of the WRS wastewater streams on orbit. The WPA influent ersatz containing 28 organic compounds[14] was prepared and allowed to reach equilibrium with the ambient lab atmosphere at 21.5 °C at approximately 9 m above nominal sea level. The ersatz organic compound concentrations were based on the average values of 19 samples returned from ISS (Expeditions 21 to 59)[14] with a TOC of 80 mg-TOC/L. the ersatz represents samples collected from Location 3 in Figure 1. A 1-mL sample from a bioreactor treating of a microbial population acclimated to the WPA wastewater was added to the 50 mL of ersatz.[18] The microbial population was not quantified in terms of cfu/mL but provided an acclimated microbial population capable of biodegrading the biodegradable TOC in the ersatz. The BOD of the bacterial cells added was measured and was less than 0.5 mg-O_2(aq)/L of BOD (data not shown here) during 24 hours. The seeded ersatz was poured gently into a 50 mL BOD bottle and capped without any headspace and no visible bubbles. A luminescent-optical dissolved oxygen sensor was calibrated in 100% relative humidity ambient air to 100% oxygen saturation (9.0 mg-O_2(aq)/L at 22.1 °C) and used to measure the dissolved oxygen concentration intermittently for 24 hours (yellow circular symbols in Figure 5). The simulation indicates that for the given test conditions and test solution used, if the WPA influent is not aerated, the dissolved oxygen will decline from 9.0 mg-O_2(aq)/L to below 1 mg-O_2(aq)/L within 24 hours in the presence of bacteria. In the following sections, the total amount of oxygen needed to fully oxidize ethanol will be quantified from theoretical considerations. Ethanol is chosen as a representative organic compound (microbial substrate) since it is the most abundant organic compound in the influent to the WPA tank,[14] as well as the most concentrated organic compound measured in condensate.[20] The same methods may be applied to calculate the oxygen requirements to fully oxidize other organic compounds in the WPA influent.

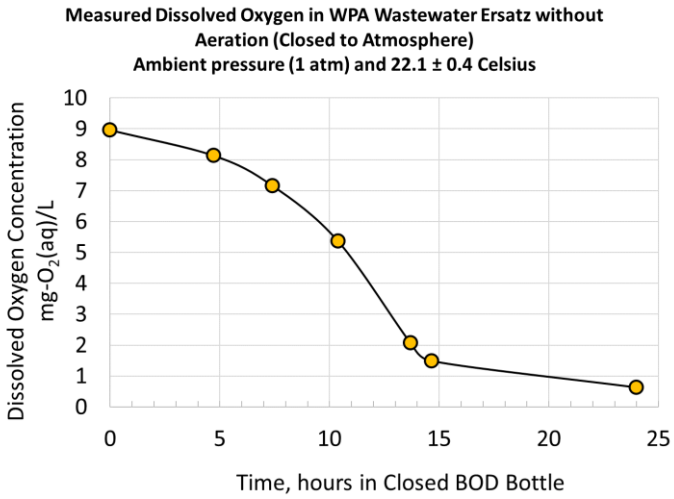


Figure 5. Rate of oxygen consumption of WPA wastewater ersatz without aeration.

The aeration module proposed in this paper would reduce the inorganic and organic loading to the MF beds, as well as the Cat Reactor, which is present at the downstream end of the WPA, where the alcohols and IPA 2-Propanol (contaminants that continuously break through the MF beds[12]) are finally oxidized to inorganic carbon. With sufficient oxygen provided by an upstream aeration module, bacteria will oxidize the alcohols and IPA to carbon dioxide and water. We note from influent and effluent data shown in Figure 2, that only partial oxidation of organics occurs within the WPA tank due to the presence of an unaerated biofilm. The carbon dioxide produced by an aerated biofilm would lower the pH and cause a shift from bicarbonate ion to carbon dioxide which could be transferred back to the cabin atmosphere if the system were open to the atmosphere. The potential reductions in inorganic ionic loading to the MF bed due to aerated microbial respiration are not included in this paper. The condensate organic loading from the MF beds to the Cat Reactor is high in TOC relative to the stringent potable water limit of 3 mg/L.[12] But the same TOC loading that is a challenge to the Cat Reactor is a very low organic loading rate for a bioreactor. If provided adequate oxygen and sufficient residence time (similar to the residence time in the current WPA tank), an aerated bioreactor has the capacity to oxidize 200 mg-TOC/L of ethanol and convert the problematic, polar VOCs to carbon dioxide at the upstream end of the treatment train (instead of at the downstream end by the Cat Reactor).[16] The upstream oxidation of the TOC would also minimize the main substrates responsible for biofilms within the WPA storage tanks and conduits.

D. Influence of Cabin Air Quality and Condensing Temperatures on Respiration Needs of Microbial Population in Condensate

The relationship between cabin air quality, humidity condensate water quality and the associated oxygen requirements to biodegrade the organic compounds is simulated with a simple model to estimate the partitioning of ethanol, a problematic VOC, into condensate. It has been demonstrated that ethanol and other volatile organics in the cabin air reach equilibrium with the newly formed condensate within the CCAA.[24,23] We can therefore calculate concentrations of dissolved ethanol and dissolved oxygen in the condensate by using Henry's Law and associated equilibrium constants, $K_{H,O2}$ for oxygen (Equation 1) and $K_{H,C2H6O}$ for ethanol (Equation 2), which are valid for 25 °Celsius (298.15 K). $[O_2(aq)]$ is molar concentration of dissolved oxygen and $[C_2H_6O(aq)]$ is molar concentration of dissolved ethanol. P_{O2} is the cabin air pressure of oxygen and P_{C2H6O} is the cabin air pressure of ethanol. We simulated the CCAA condensing temperatures ranging from 4.4 °C to 14 °C to include nominal condensing temperatures in the US Segment (4.4 °C) and the Russian segment (14 °C), respectively.[24]

$$K_{H,O2} = \frac{[O_2(aq)]}{P_{O2}} \qquad (1)$$

$$K_{H,C2H6O} = \frac{[C_2H_6O(aq)]}{P_{C2H6O}} \quad (2)$$

To simulate gas-liquid equilibrium of ethanol or oxygen for temperatures other than 25 °C, the *van't Hoff* equation is used (Equation 3).

$$ln\left(\frac{K_{H,T2}}{K_{H,T1}}\right) = \frac{\Delta H^0_{rxn}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \quad (3)$$

Where temperature, T, is in Kelvin, R is the universal gas constant, (0.08206 mole/(L·atm), and ΔH^0_{rxn} is the enthalpy of the reaction.

Values for Henry's Constants and their temperature adjustment factors are given in Table 2.

Table 2. Values of Gas-Liquid Equilibrium Parameters for Henry's Law.[25]

Compound	K_H, mole/(L·atm) at 25°C (298.15K)	$\frac{\Delta H^0_{rxn}}{R}$, Kelvin	Molar Mass, gram/mole
Oxygen, O_2	$1.3 \cdot 10^{-3} \pm 4.31 \cdot 10^{-5}$ n = 14	1515 ± 157 n = 13	32.00
Ethanol, C_2H_6O	190 ± 7 n = 14	6283 ± 346, n = 12	46.07

The reaction to represent microbial respiration of ethanol is based on a molar balancing of carbon, oxygen, and hydrogen and is given by Equation 4. We note that this reaction does not include the effects of cell synthesis on biochemical oxygen demand. The effects of oxygen used by bacteria to oxidize ethanol's organic carbon to cellular carbon will be quantified in future simulations once the yield coefficient is determined by experiment.

$$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O \quad (4)$$

Based on this reaction, the oxygen required by bacteria to respire ethanol, C_2H_6O, completely to carbon dioxide is 3 mole-O_2/mole-C_2H_6O, or 2.08 g-O_2/g-C_2H_6O. We also note that the ethanol molecule is 52.1% carbon by mass, so for a given ethanol concentration in the condensate we can calculate total organic carbon (TOC) in the ethanol molecule and in the condensate.

Here we extend the previously published work that calculated ethanol concentrations in condensate at two discrete temperatures (4.4 °C and 14 °C)[23] to cover the continuous range of 4.4 °C to 14 °C, since CCAAs can operate at a range of temperatures. In addition, for the first time, we introduce and include dissolved oxygen concentrations and the biochemical oxygen demand of ethanol to calculate an oxygen deficit for microbial oxidization of ethanol to carbon dioxide. The oxygen deficit in the liquid condensate is calculated as a function of condensing temperatures and cabin air ethanol concentrations. We note that dissolve oxygen and BOD are generally ignored as water quality parameters on ISS but are included here and deemed important in understanding some of the current operational issues on ISS (biofilm in WPA tank and the limited capacity of the WRS to process condensate's organic loading). These parameters will also be important if bioregenerative subsystems are ever integrated into ECLSS.

Figure 6 shows the impact of the temperature of condensation in the CCAAs on the concentration of dissolved ethanol in the condensate. The typical temperature of condensation in the US Segment on ISS is marked by the markers at 4.4 °Celsius. The typical temperature of condensation in the Russian Segment is 14 °Celsius, and it is also denoted by markers. We observe that the amount of ethanol in the condensate is about half as much in the Russian Segment condensate compared to the condensate in the US condensate. Whereas the concentration of dissolved oxygen in the condensates is not significantly different in the US or Russian Segment condensate.

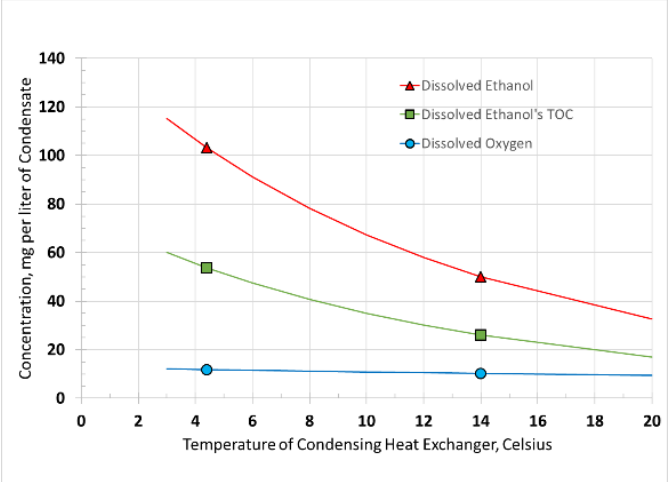


Figure 6 Effect of CCAA Temperature on Dissolved Ethanol and Oxygen concentrations in Condensate for typical ISS Cabin Atmospheric Concentration of 5 mg-ethanol/m^3 and PO2 = 0.21 atm

Figure 7 shows the concentrations of ethanol in the condensate as a function of both condensing temperature and cabin air concentrations of ethanol. Because the Russian and US segments' atmospheres are well-mixed, they typically have about the same cabin air concentrations of organic compounds. As discussed previously, the value of 5 mg/m^3 is a cabin air ethanol concentration that begins to pose concerns with overloading the treatment capacity of the water recovery system.[20,23] For reference, when the ISS cabin air ethanol concentration is 5 mg/m^3, the total ethanol emission rate to the atmosphere was calculated in 2016 to be 3.34 g/day.[23] At this generation rate, 2.65 g/day (79%) was removed by the air revitalization systems and 0.68 g/day was removed by the condensate collection systems (21%). The chart shows the ethanol loading in the condensate is highly dependent on cabin air concentrations and temperature of condensation.

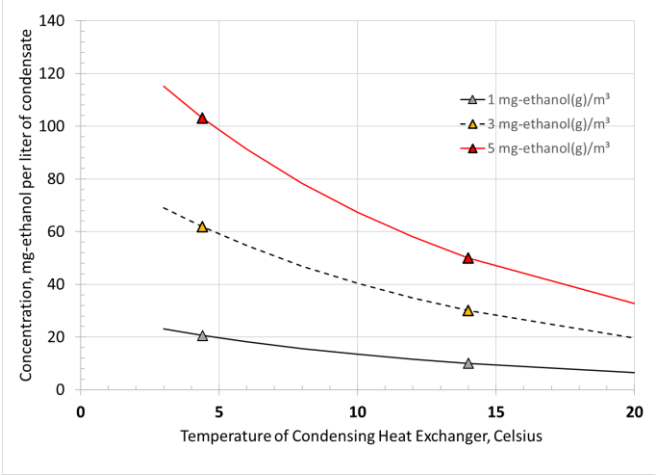


Figure 7 Effect of CCAA Temperature on Dissolved Ethanol concentration in Condensate for ISS Cabin Atmospheric Concentrations of 1, 3, 5 mg-ethanol/m^3.

Figure 8 shows the concentrations of dissolved oxygen that would be required to respire (oxidize) the ethanol to carbon dioxide as a function of both condensing temperature and cabin air concentrations. The oxygen required to oxidize a given concentration of ethanol in the condensate is based on Equation 4.

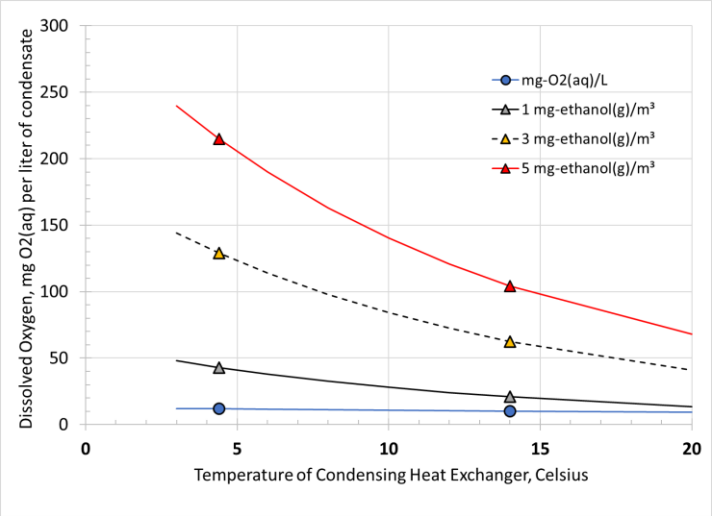


Figure 8 Effect of CCAA Temperature on Dissolved Oxygen and Oxygen Required to Respire Ethanol.

Figure 9 shows the dissolved oxygen deficit that the microbial population would experience for the given ethanol concentrations (1, 3, and 5 mg/m^3 in the cabin air) for the typical ISS oxygen partial pressure of 0.21 atm. The deficit is defined as the concentration of the oxygen required to fully oxidize ethanol (see Figure 8) minus the dissolved oxygen concentrations for a given condensation temperature (see bottom blue line of Figure 8). For the worst case of 5 mg/m3 ethanol in cabin air and the US Segment condensation temperature of 4.4 °C, the oxygen deficit is about 200 mg-O_2(aq)/L. The oxygen deficits are lower for the Russian segment condensation temperature of 14 °C, ranging from 11 mg-O_2(aq)/L for 1 mg-ethanol/m^3 to 94 mg-O_2(aq)/L for 5 mg-ethanol/m^3. In all cases, complete oxidation of these normal cabin air concentrations of ethanol is not possible without additional aeration. With additional aeration, the oxygen deficit would approach zero as the microbes are given sufficient oxygen to oxidize the ethanol.

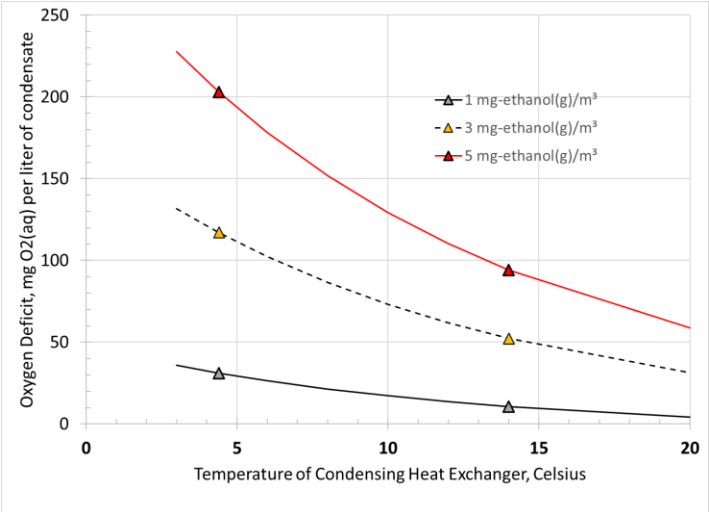


Figure 9 Effect of CCAA Temperature on Dissolved Oxygen Deficit to Oxidize Ethanol to CO_2.

IV. Discussion

The implementation of an aeration module upstream of the WPA wastewater tank would provide the simplest location with the lowest risks to introduce a managed microbial population to treat the organic loading in condensate, because the basic biochemical transformation and bacterial solids are already present in the system (Figure 1). The current WPA wastewater tank, which receives both condensate and urine distillate at approximately equal flow rates, has been shown to partially oxidize the organics present, including the problematic VOCs (ethanol) as shown in Figure 2.[14]

Concerns related to fixed film bioreactors include their relatively large size (requiring about 1 to 3 days of detention time for condensate), their start up durations and protocols, their production of soluble microbial products into the waste stream, and the potential shedding of bacterial cells into the waste steam. In terms of size, the long-term solution could be to convert waste storage tanks, such as the WPA wastewater tank to an AM, allowing gas-liquid exchange to optimize the bacterial respiration by getting oxygen into the water and carbon dioxide out of the water. Although this is an active area of research, and is well suited for an SBIR topic, the current technical options are at a low TRL. We propose the most expedient placement of an AM relative to the heritage WPA treatment train would be immediately downstream of the CCAAs to collect data and gain experience. But another good location would be immediately upstream of the WPA wastewater tank, which receives both condensate and urine distillate in about equal volumes.

The TTU bioreactors are microgravity compatible and at a current TRL of about 4. Although the remaining concerns are constraints, they are already being managed in the current heritage ISS WRS WPA that has an active and extensive microbial population in the WPA wastewater tank. The sloughed bacteria are removed in filter assembly, and the soluble microbial products are captured on the activated carbon in the MF bed. Regarding start up, the bacterial population in the tank could be used to inoculate a new AM, but freeze dried, condensate acclimated populations are also available from Texas Tech for a pristine water recovery system.

In advancing the TRL from 4, the main engineering challenges are how to aerate the system and how to provide mixing of liquid within the AM and optimizing aeration (oxygen mass transport). Several options are available for aeration: pure oxygen, flowing cabin air, and passive aeration using cabin air without air pumps or additional air pressure by strategic placement of the AM within the well mixed air of ISS. Liquid mixing during ground testing is normally provided by a recycle pump, which recirculates condensate throughout the bioreactor.

One other design parameter to be optimized is the ideal geometry and flow conditions to minimize free floating bacteria from exiting in the effluent at the outlet pipe of the bioreactor when it is in micro-gravity. During ground testing, it is very difficult to prevent natural sedimentation of bacterial flocs (preventing them from flowing out of the AM), which would not happen in microgravity. This would not be as big of a challenge for AMs installed in partial gravity habitats, where gravity would provide sedimentation of flocs, so they don't exit the module. The current unaerated microbial population on ISS sheds small amounts of biofilm that are managed by the 300-micron filter assembly downstream of the WPA wastewater tank. An AM placed upstream of any storage tank would provide an oxygenated attachment surface to promote a stable and healthy biofilm with significantly reduced death and detachment of microbial flocs compared to the current unaerated biofilm in the tank.

V. Summary

This paper has defined a technical framework for ECLS systems in terms of life support technologies for humans, microbes, and plants. We have provided background on the importance of aeration for waste streams and their naturally occurring microbial populations. We propose that the integration of a microgravity compatible, bubbleless aeration module would support a healthy biofilm to oxidize organics in the condensate to carbon dioxide. The aeration module would provide supplemental dissolved oxygen directly to the base of the biofilm to meet the oxygen demand quantified in this paper for the most abundant organic compound in condensate, ethanol. The same method and simulations could be applied to the other organic compounds in condensate. We have reviewed the literature that demonstrates the success in ground testing of aeration modules treating simulated waste streams, such as condensate. We also calculated the impacts of condensing temperatures on the ethanol concentrations and associated oxygen demand in newly condensed water. Colder condensing temperatures (e.g. 4.4 °C) result in higher concentrations of organics (e.g. ethanol) and larger oxygen deficits that warmer condensing temperatures. We propose that integrating an aeration module into the current ISS WRS is a viable option for resolving the uncontrolled biofilm issues in the WPA

wastewater tank. Installing an aeration model would maintain the beneficial oxidation reactions of organics that are already occurring in the WPA storage tank but are limited by inadequate aeration that results in incomplete microbial oxidation of organics in the WPA wastewater. With adequate aeration and an oxygenated attachment surface, a healthy microbial population would completely oxidize problematic volatile organic compounds such as ethanol, that have the potential to overload the current WRS when cabin air concentrations exceed 5 mg-ethanol/m^3. Finally, the aeration module would provide a critical step in adding an engineered, bioregenerative component to the current ISS ECLSS.

Acknowledgments

The authors acknowledge and appreciate the valuable contributions from their colleagues at NASA Johnson Space Center. The authors thank the anonymous ICES reviewers for making extensive and thoughtful reviews of the manuscript and providing very insightful comments and suggestions.

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